Full Jet-Reconstruction in STAR

Jörn Putschke

for the STAR collaboration

(Yale University)

South and North Six Shooter, Indian Creek, Utah, 2007

Outline

Jets in p+p and d+Au reference

- Inclusive jet spectrum and fragmentation functions in p+p
- A look at the underlying p+p event (Intial/Final-state radiation)
- Nuclear k_T in d+Au

Jets in heavy-ion collisions

- Inclusive jet spectrum and jet R_{AA}
- Jet energy profile
- Di-Jet coincidence/Hadron-Jet measurements
- (Modified) Fragmentation function
- Jet-Hadron correlations

Towards a complete study of jet-quenching

Di-hadrons are <u>indirect</u> measurements of jet quenching !

To study the full spectrum of jet quenching in an unbiased way we need new techniques

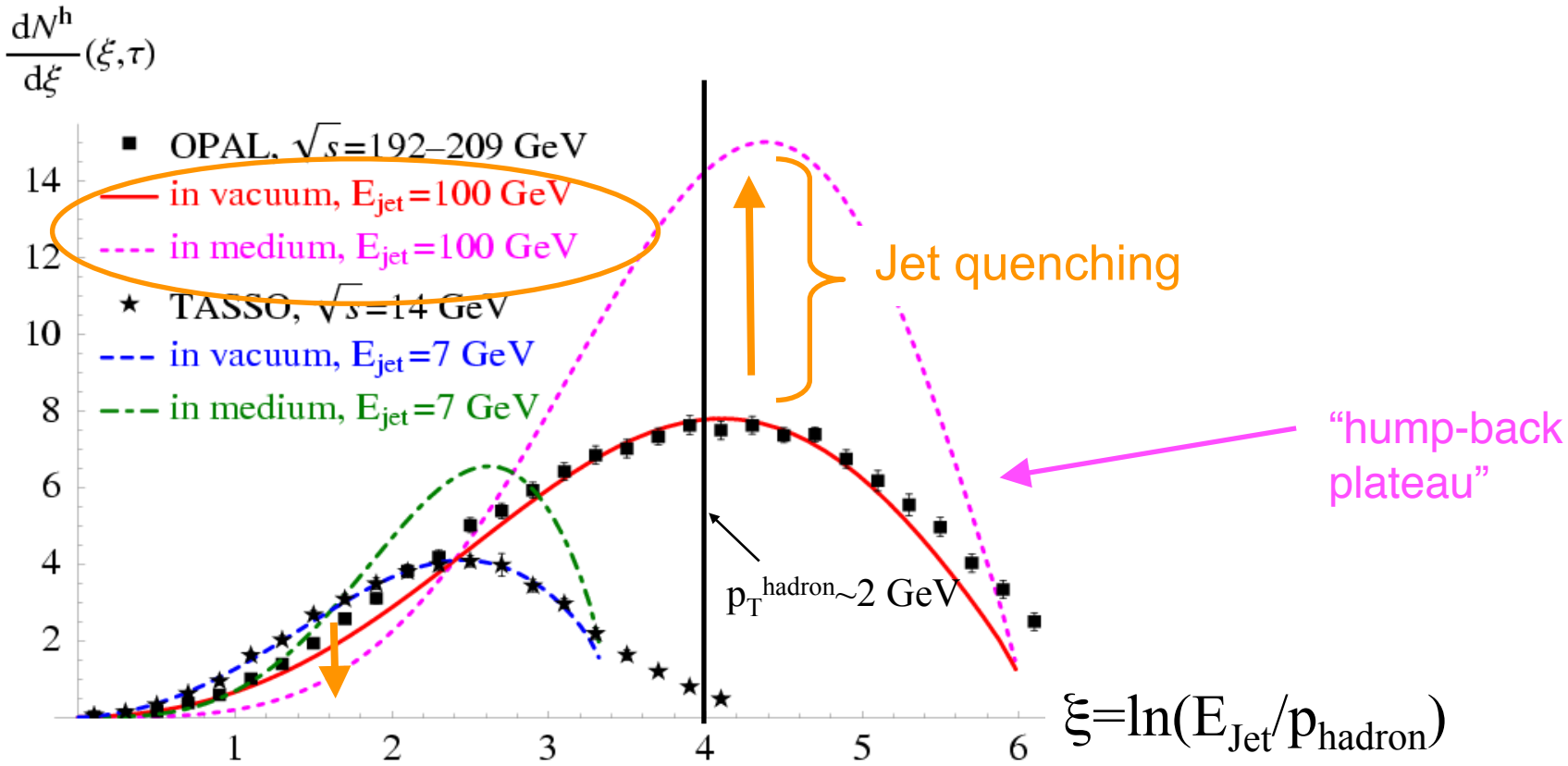
<u>Two approaches:</u>

1. γ-jet: clean, but limited kinematic reach due to x-section

2. Full jet reconstruction: large kinematic reach, but complex analysis

Benchmark observable: modified fragmentation function

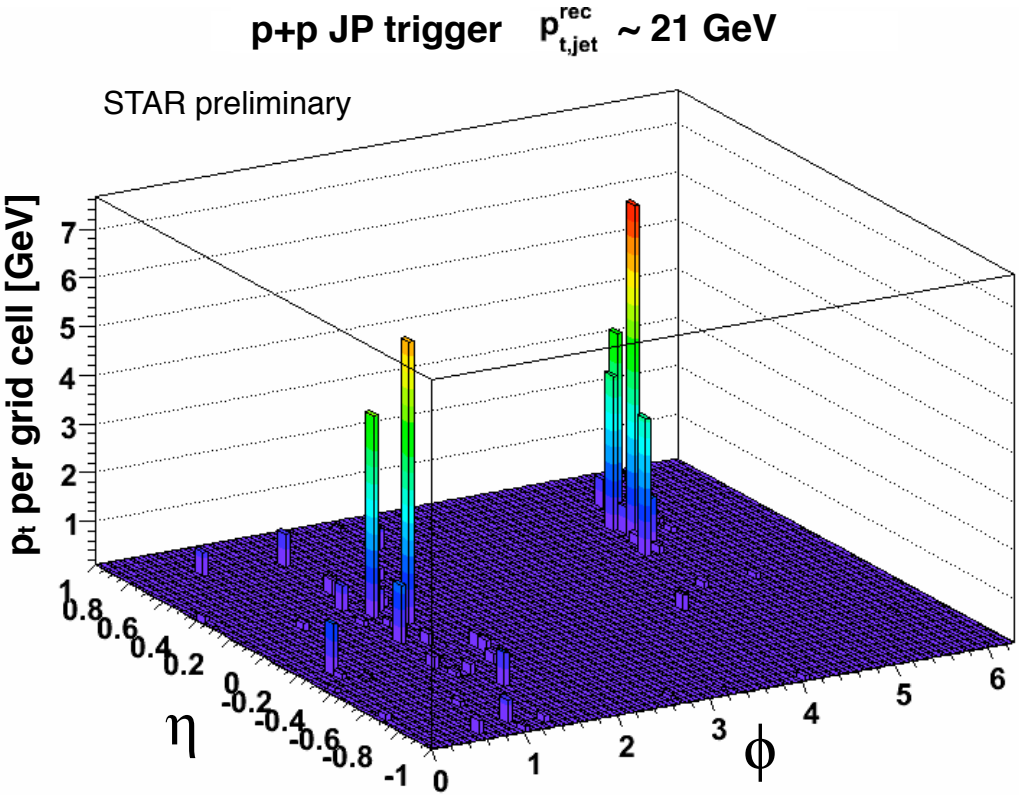
- MLLA: good description of vacuum fragmentation (basis of PYTHIA)
- Introduce medium effects at parton splitting *Borghini and Wiedemann, hep-ph/0506218*



Jet quenching ⇒ fragmentation should be strongly modified at p_T^{hadron}~1-5 GeV

Can we measure this at RHIC @ 200 GeV ?

Experimental setup/data-sets



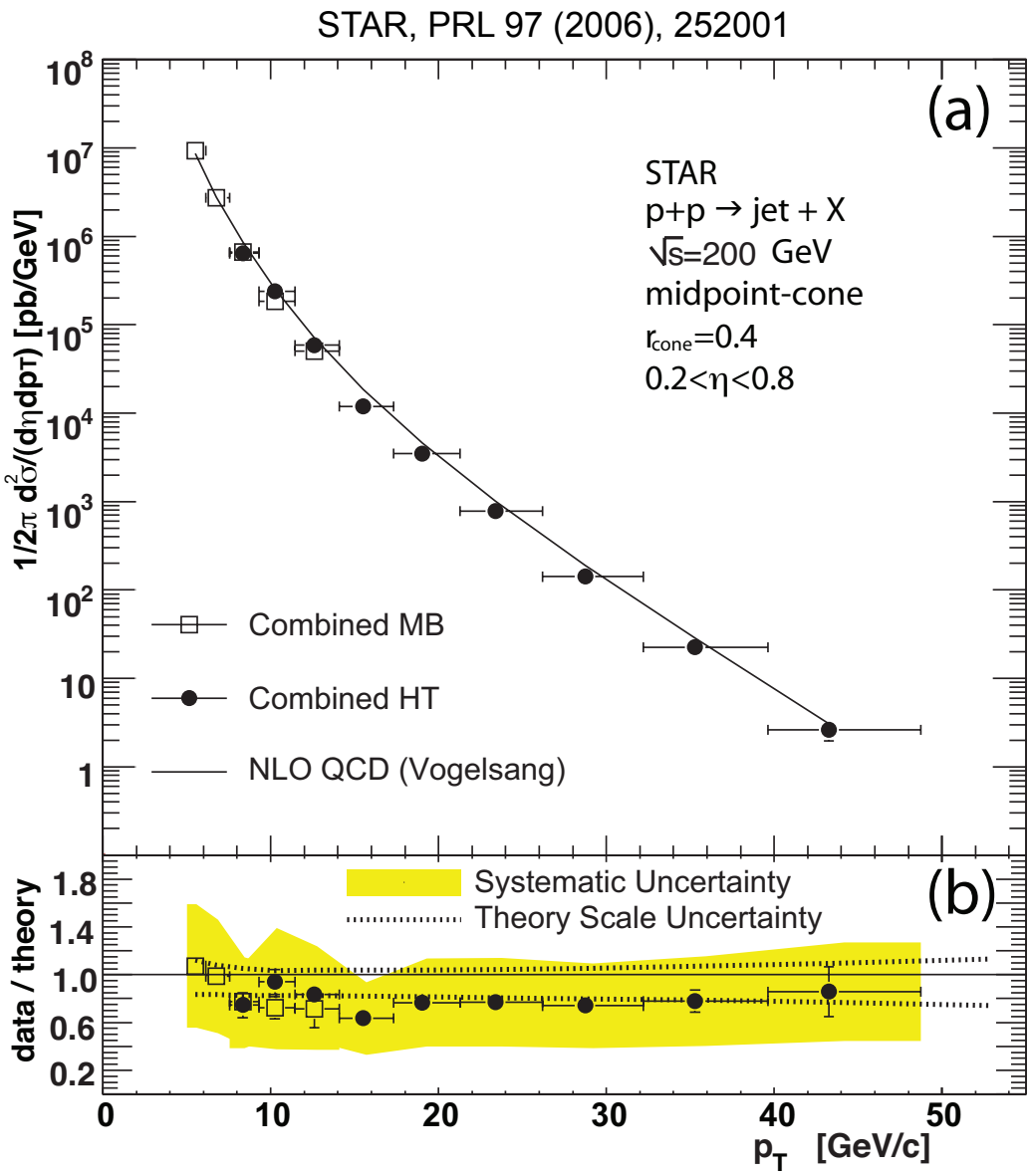
Jet-finding is performed on a "grid" using p_t/E_t from:

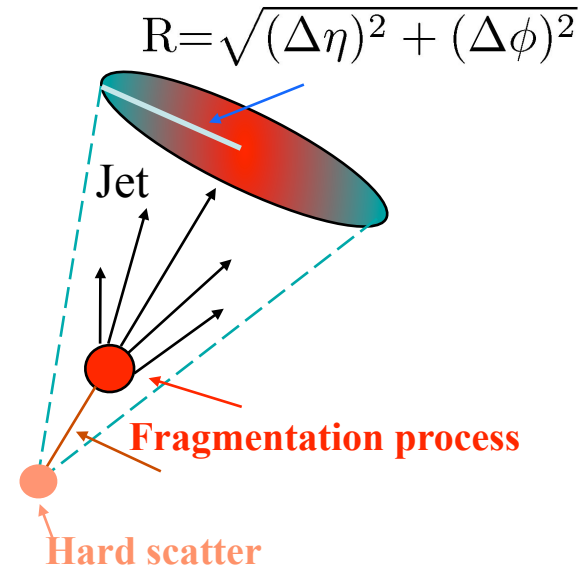
- charged particle p_t (TPC)
- neutral tower E_t 0.05x0.05 (ηxϕ) (EMC)
  - corrected for hadronic energy.
  - Electron correction applied.
  - EMC provides fast trigger.

Analyzed STAR data-sets:

- *p+p (2006) High-Tower (HT) trigger (single tower E_t>5.4 GeV)*
- p+p (2006) Jet-Patch (JP) trigger (ηxϕ=1x1 with sum E_t>8 GeV)
- *Au+Au (2007) High-Tower (HT) trigger (E_t>5.4 GeV)*
- Au+Au (2007) Minimum-Bias (MB) trigger

Reference: jet x-section in p+p collisions





Jet cross-section in p+p is well described in pQCD framework over 7 orders of magnitude

Look now at the real jet fragmentation function: $z=p_t/E_{jet}$ and $\xi=\ln(1/z)$

Reference: Charged ξ Jet Fragmentation in p+p

JP trigger

$|\eta_{jet}|<1-R$

Data not corrected for particle level

Increasing Jet Energy

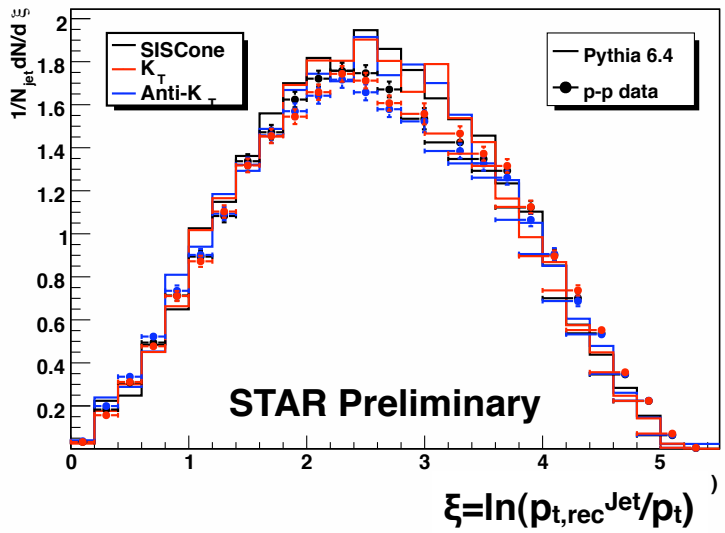
$20<E^{reco}<30$ GeV

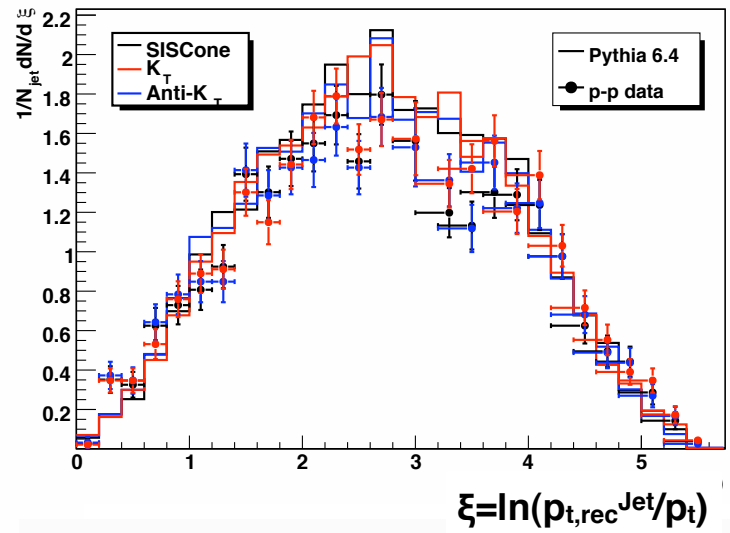
$30<E^{reco}<40$ GeV

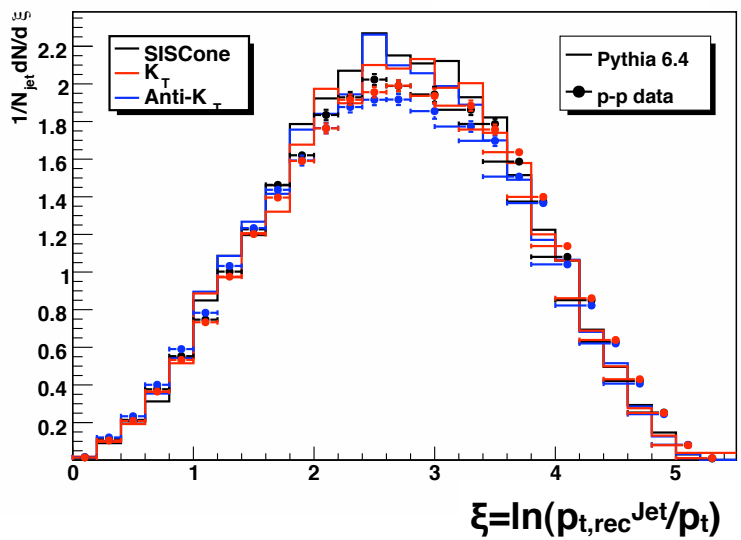
R<0.4

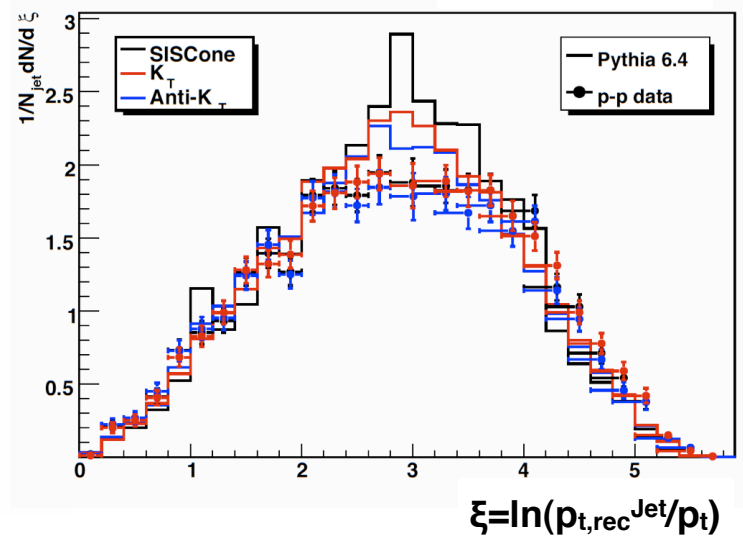
R<0.7

Increasing Cone R



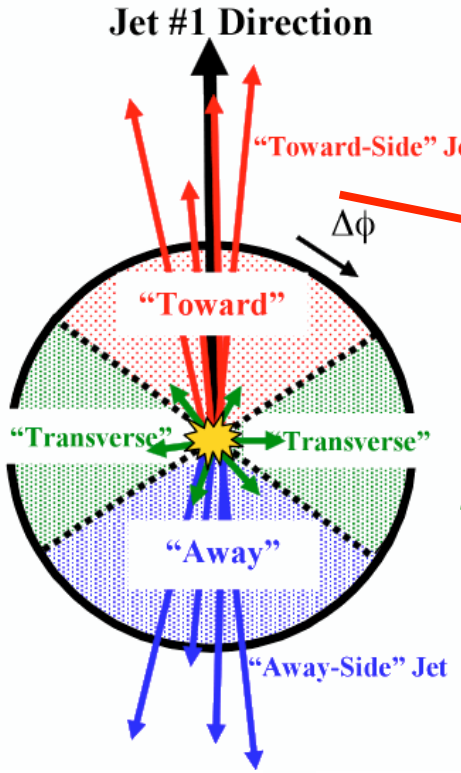




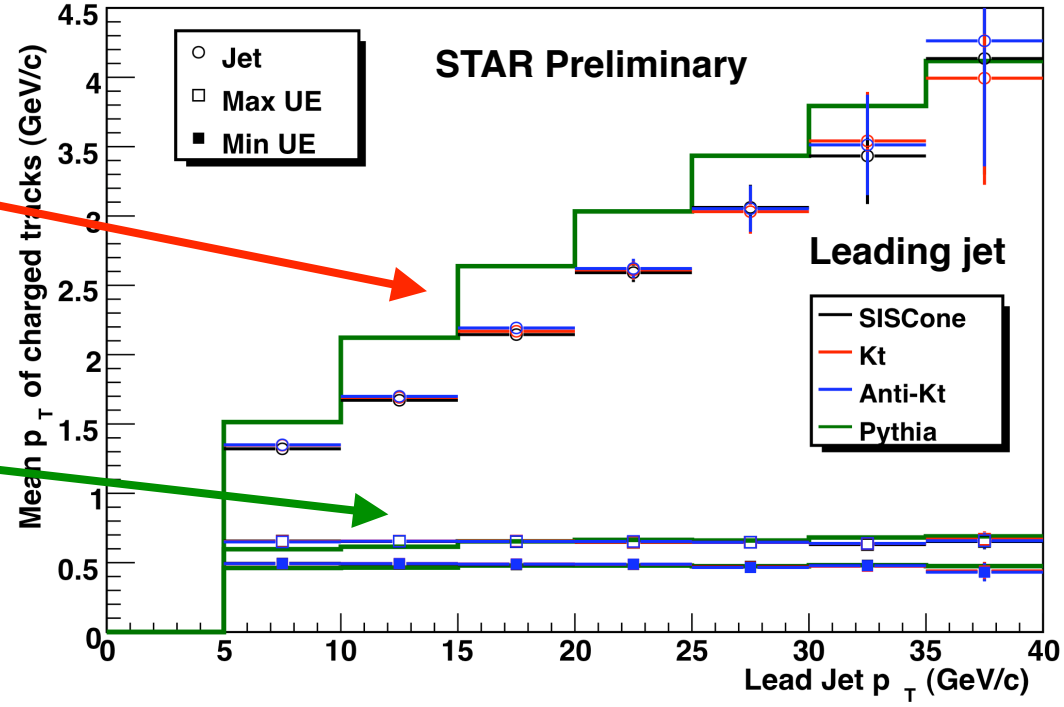


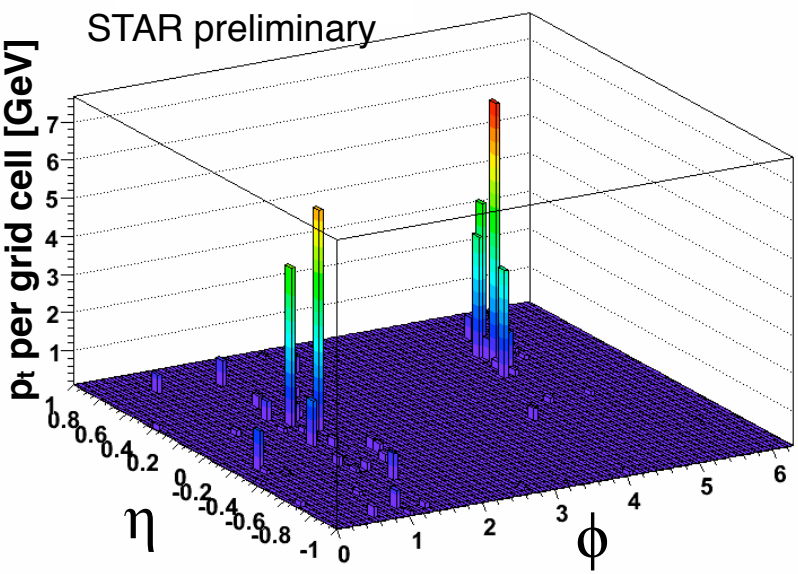
Reasonable agreement with Pythia+Geant simulations for different R and jet p_t

The underlying event in p+p collisions



p+p JP trigger $p_{t,jet}^{rec}$ ~ 21 GeV





- Underlying event is decoupled from the hard scattering
- Small initial and final state radiation at large angles at RHIC energies

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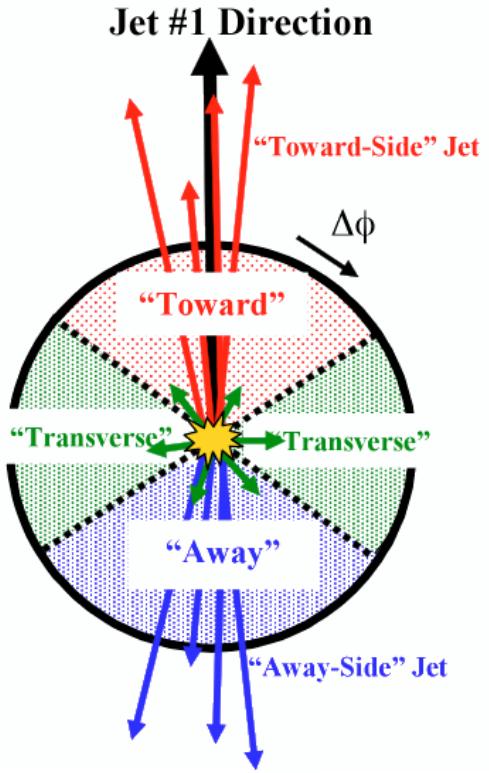

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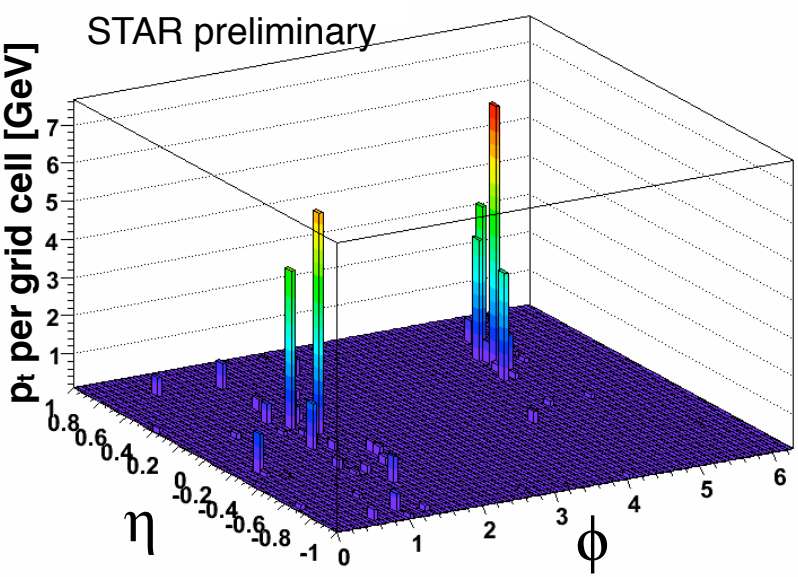

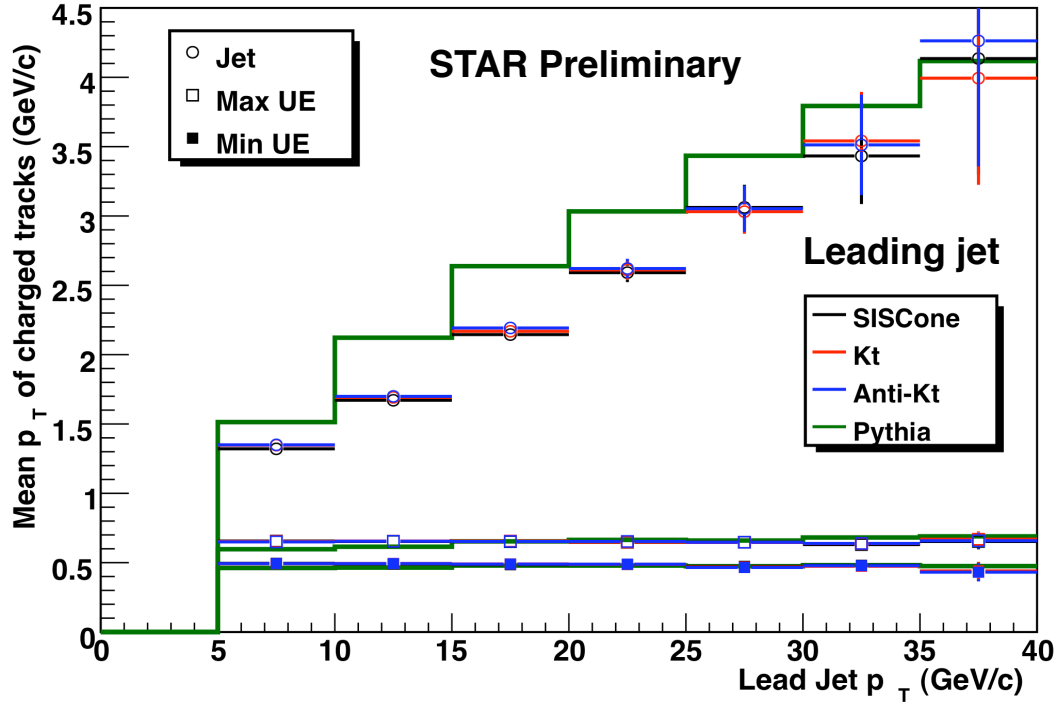

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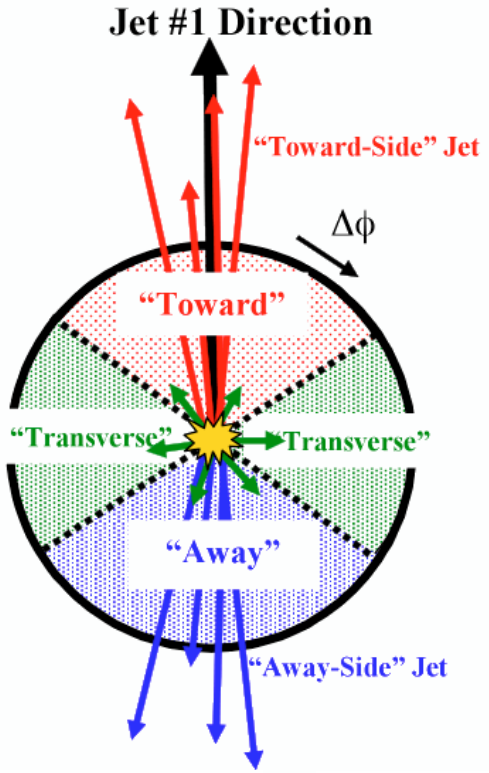

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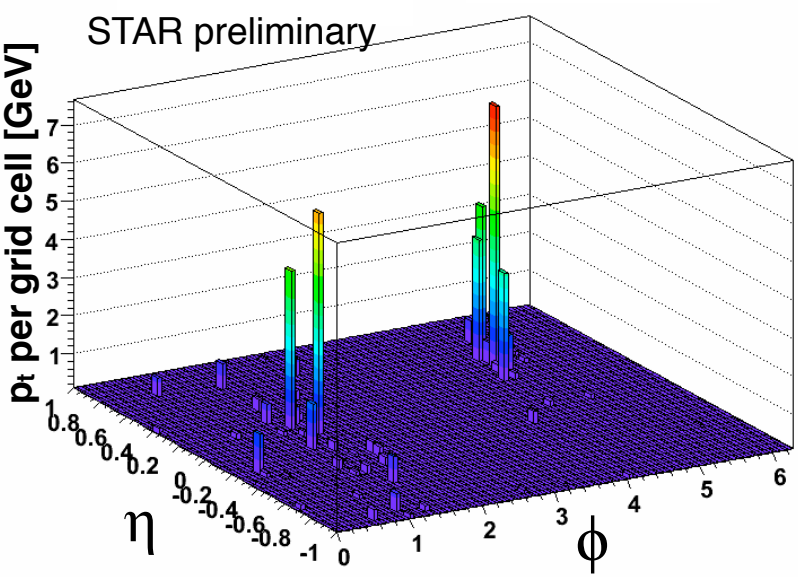

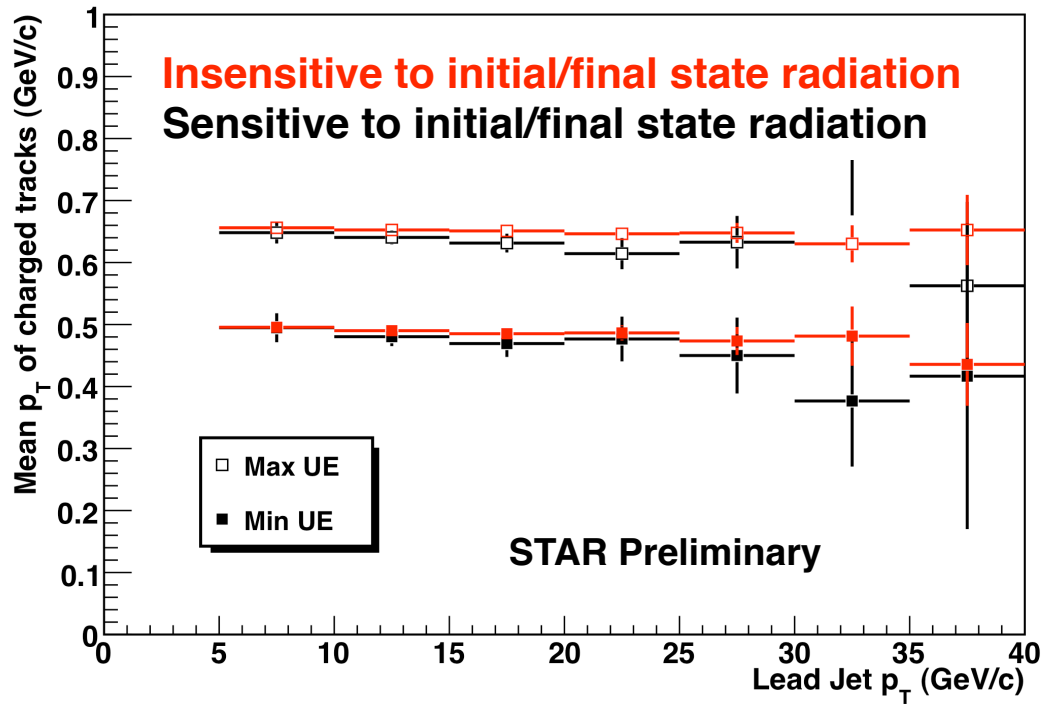

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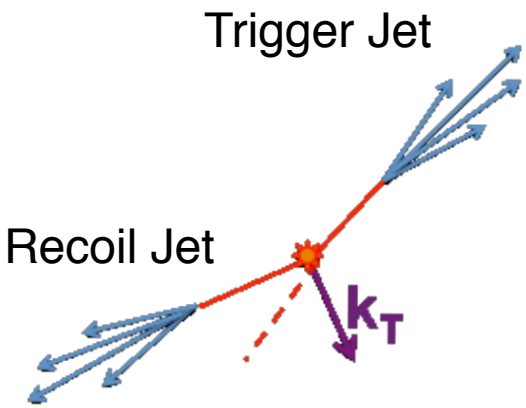
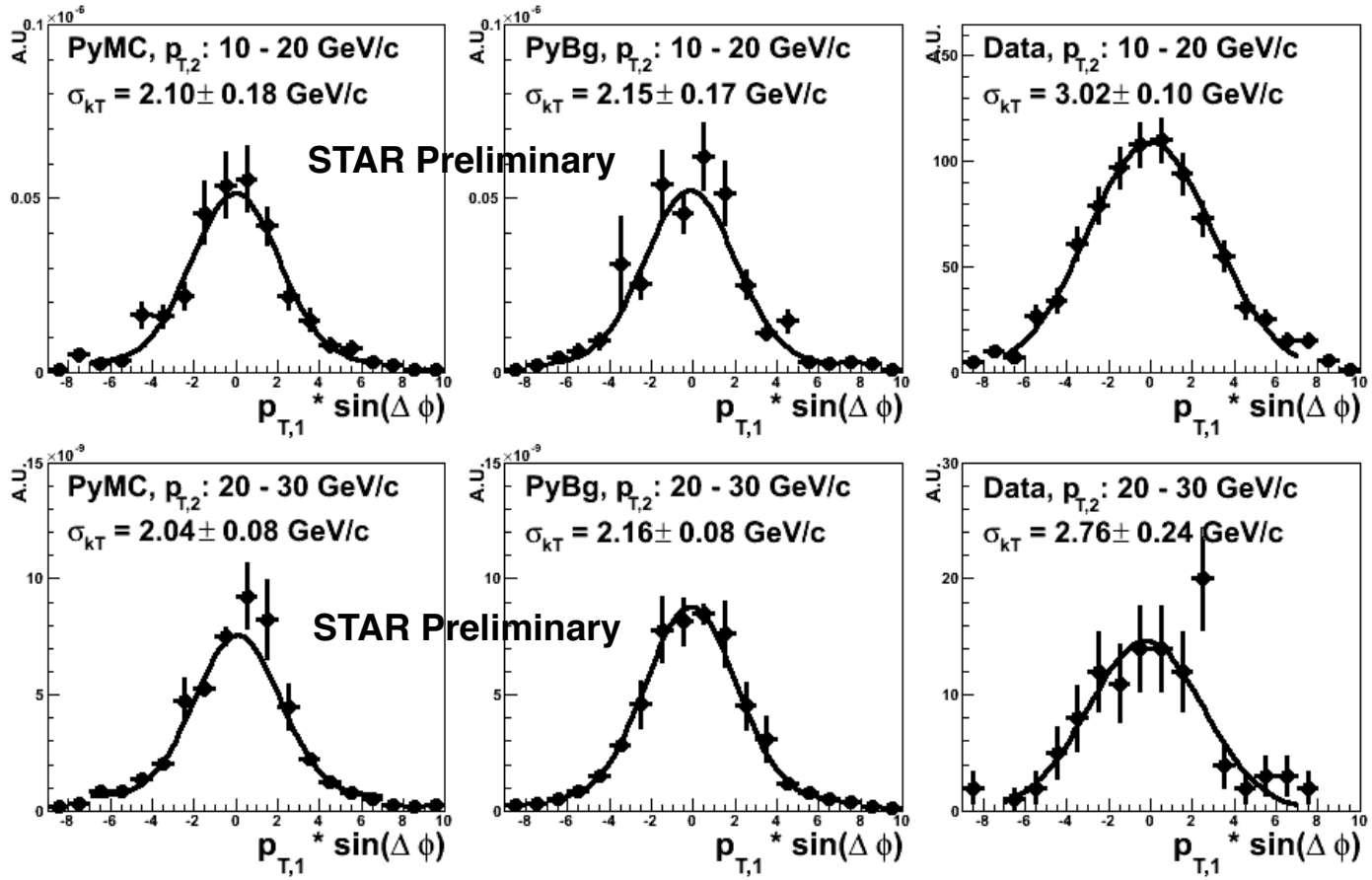
Measurement of nuclear k_T via di-jets in d+Au



$k_T = P_{T,1} * \sin(\Delta\phi)$

Pythia | Pythia+GEANT+dAu bkg. | **d+Au data**



Measure σ_{kT} via di-jets in d+Au (p+p):

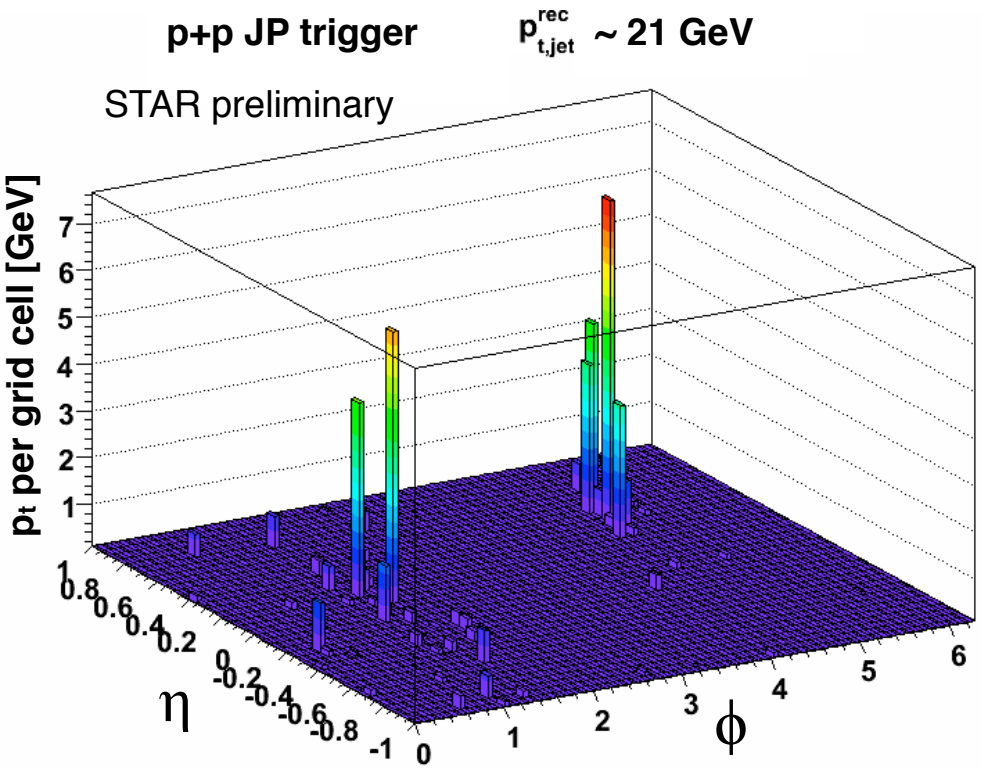
p+p: σ_{kT}=2.08 ± 0.12 (stat) ± 0.13 (sys) GeV/c

T. Henry (STAR Collaboration), PhD thesis, Texas A&M University, 2006

d+Au (0-20%): σ_{kT}=3.0 ± 0.1 (stat) ± 0.4 (sys) GeV/c (further systematics under evaluation)

Measurement of the initial state k_T in d+Au collisions feasible with the current data !

Full-Jet reconstruction in HI collisions



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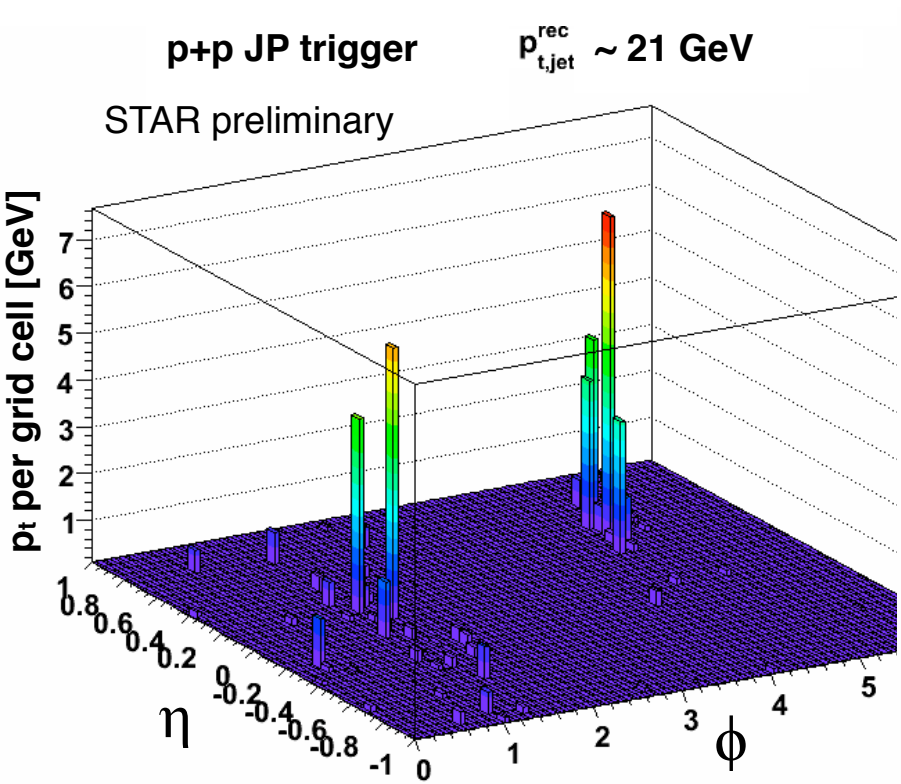

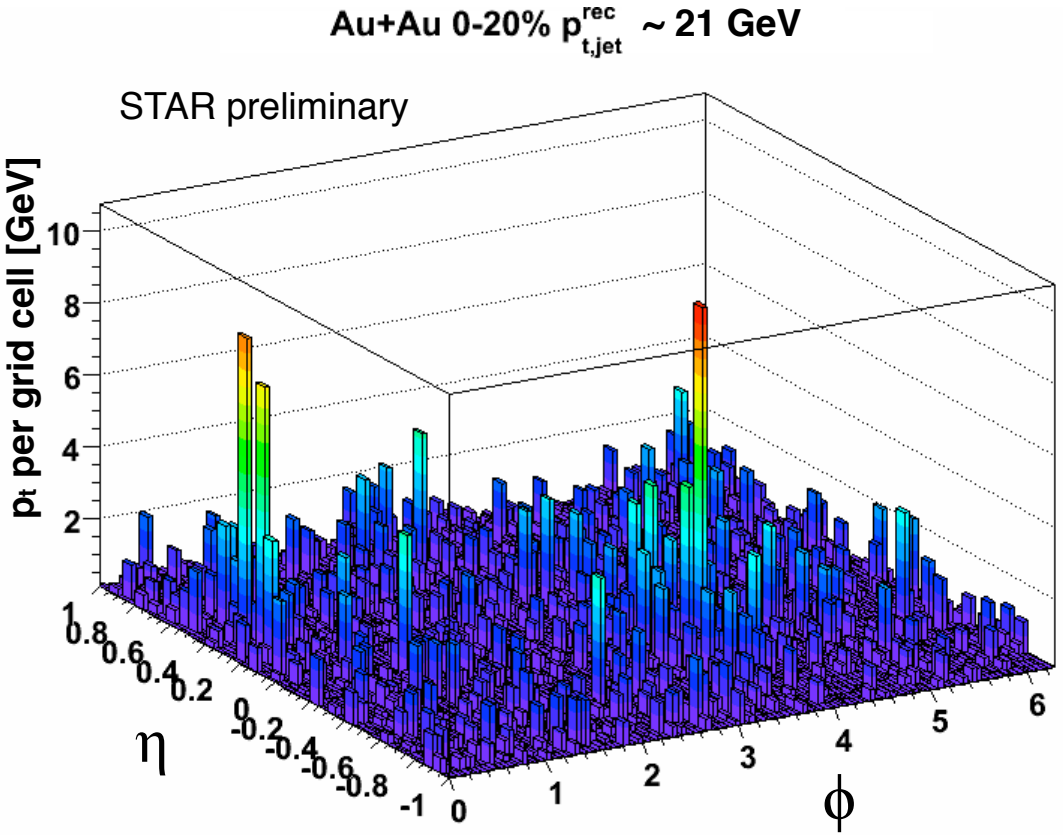

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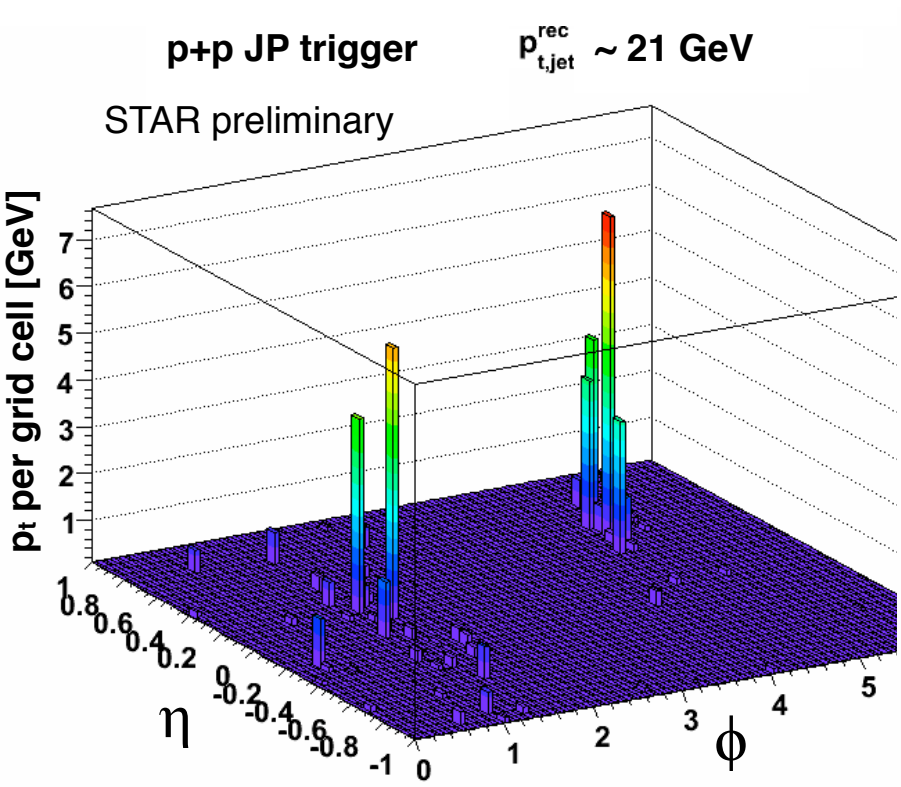
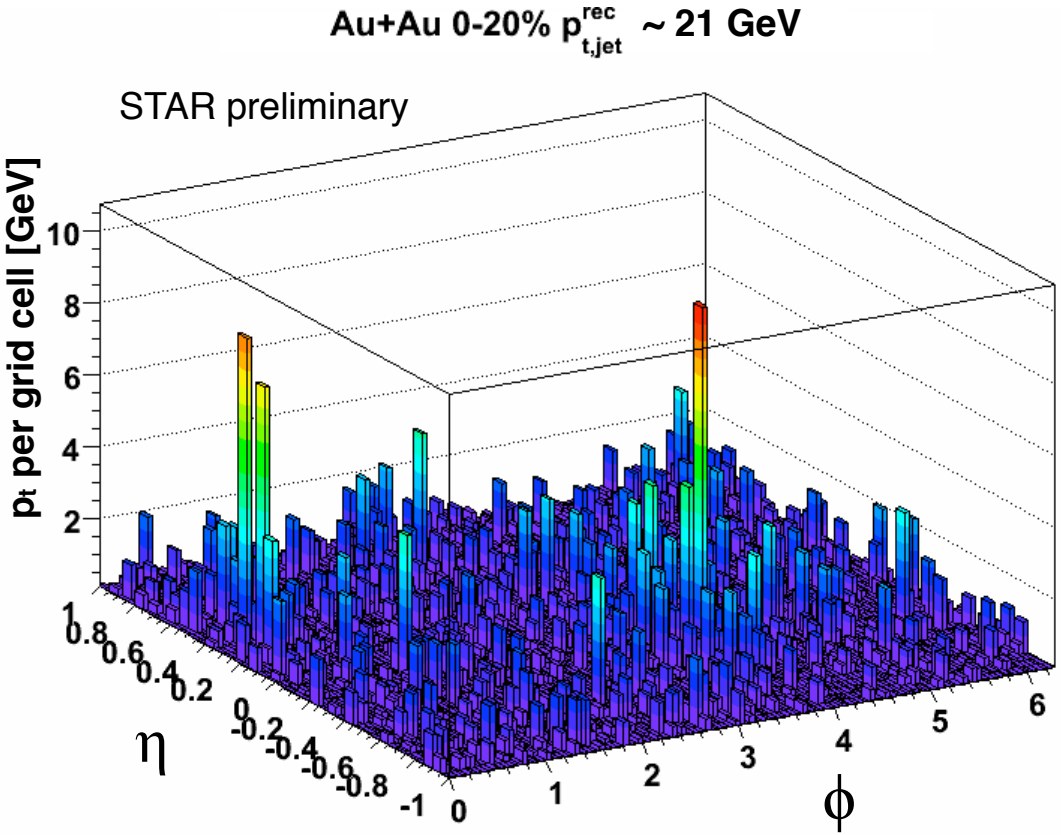
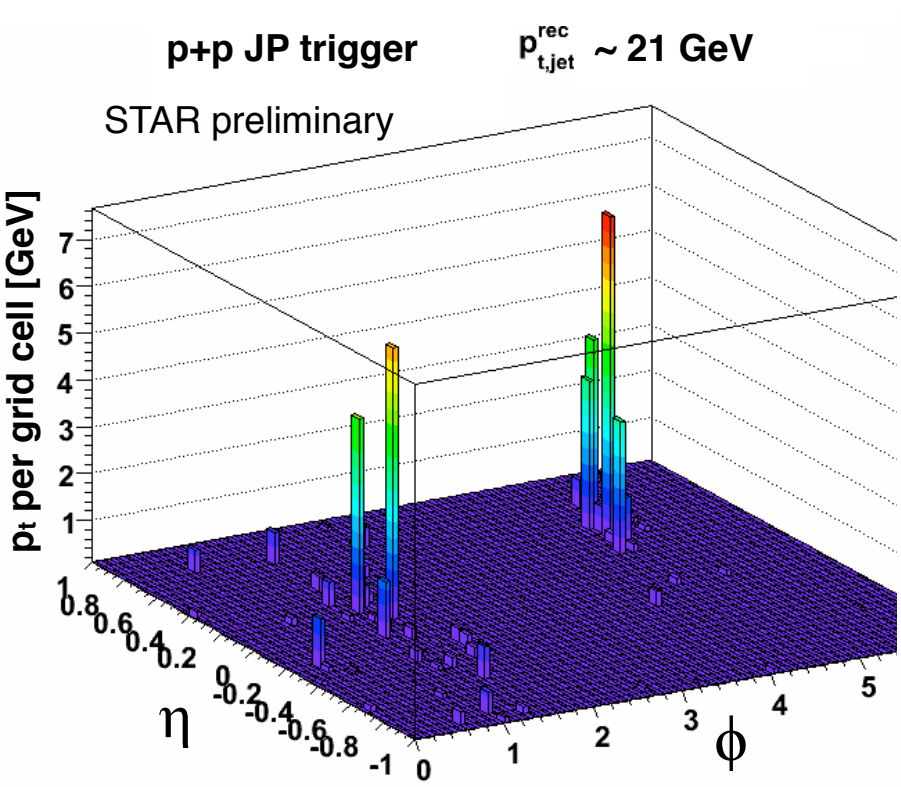
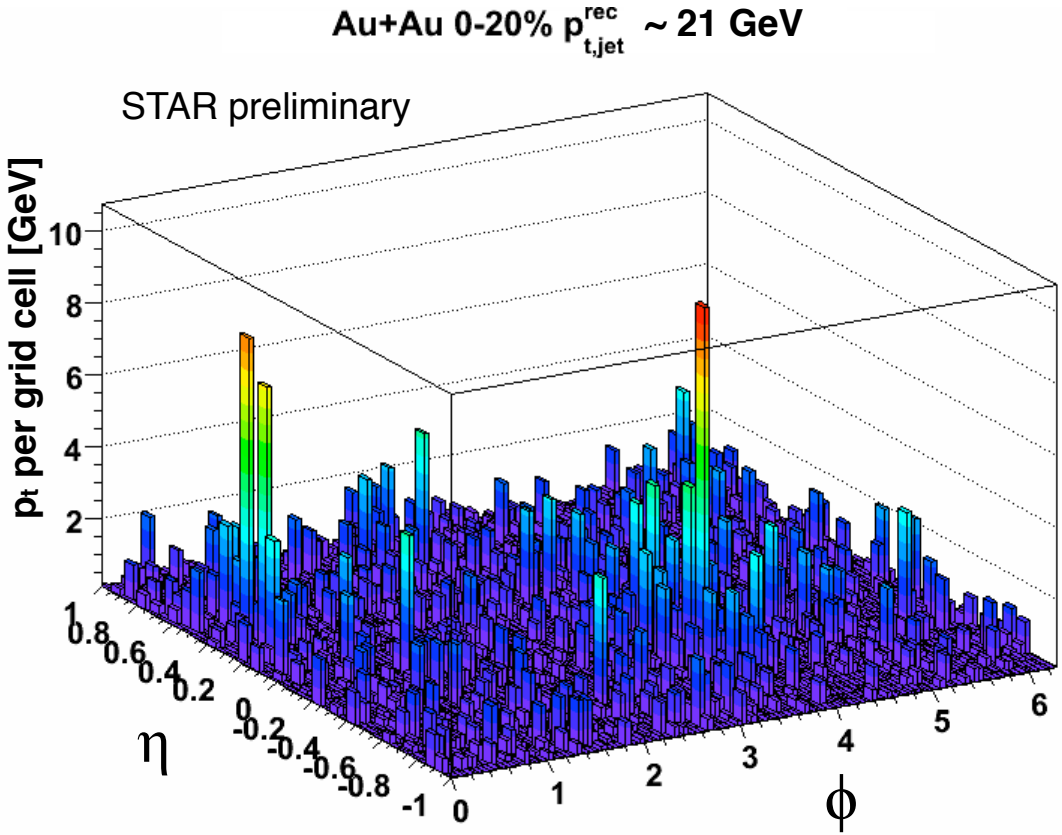




Full jet reconstruction in HI collisions is a challenge due to the underlying background !

Full-Jet reconstruction in HI collisions





Full jet reconstruction in HI collisions is a challenge due to the underlying background !

<u>But:</u> We have all the tools (FastJet jetfinder) and methods (unfolding) to correct for background and fluctuations in a data driven approach

Matteo Cacciari, Gavin P. Salam and Gregory Soyez; arXiv: 0802.1188

Systematic corrections

Trigger corrections:

- p+p trigger bias correction

Particle level corrections:

- Detector effects: efficiency and pT resolution
- "Double* counting" of particle energies
  - * electrons: - double; hadrons: - showering corrections
  - All towers matched to primary tracks are removed from the analysis

Jet level corrections:

- Spectrum shift:
  - Unobserved energy
  - TPC tracking efficiency
- EMC calibration (dominant uncertainty in p+p)
- Jet pT resolution
- Underlying event (dominant uncertainty in Au+Au)

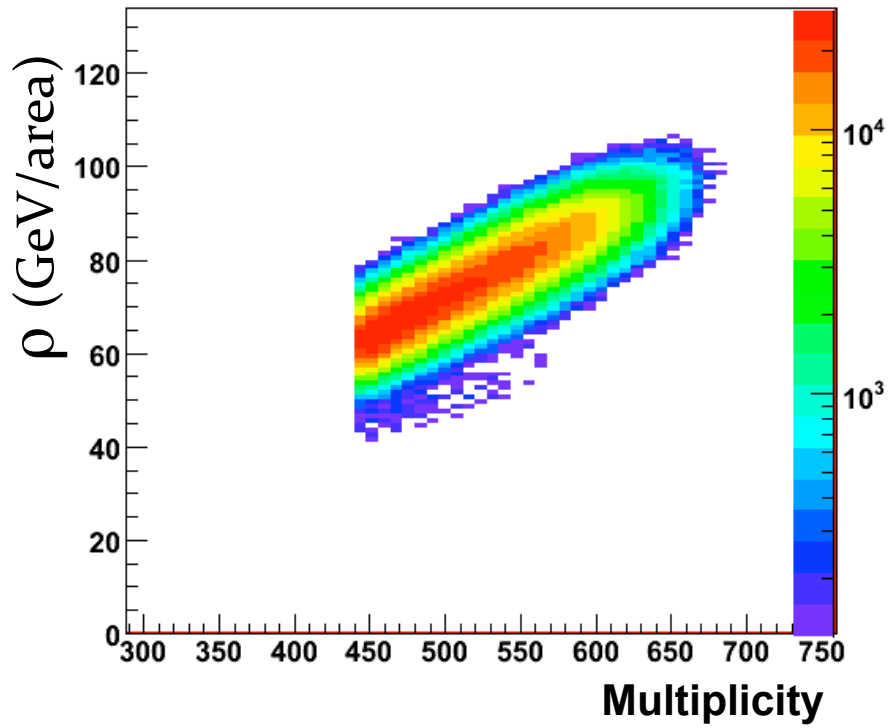
Full assessment of jet energy scale uncertainties

Data driven correction scheme !

Event Background in central Au+Au collisions

Event-by-event basis:

p_T (Jet Measured) ~ p_T (Jet) + ρ A ± σ √A



Underlying background

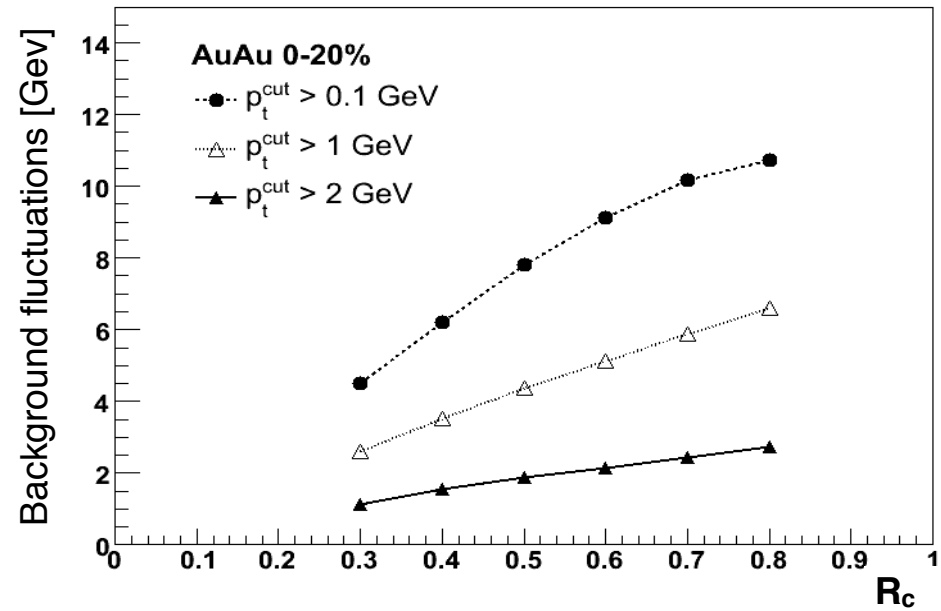
ρ is the background energy per unit area
A is the jet area
ρ, A estimated from FastJet algorithm

~ 45 GeV for R_C=0.4
(S/B ~0.5 for 20 GeV jet)

Substantial region-to-region background fluctuations

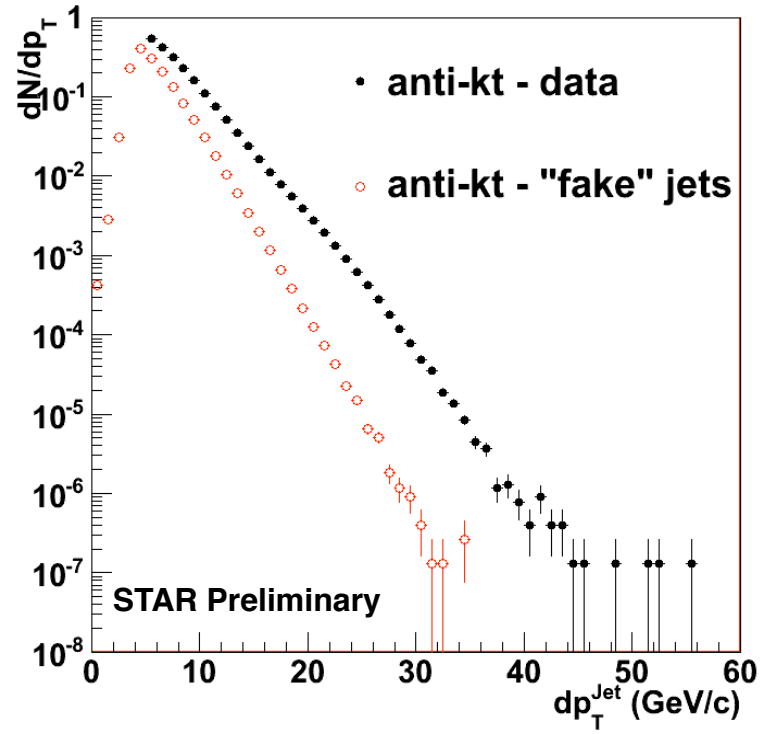
comparable magnitude in σ from FastJet and naïve random cones

~ 6-7 GeV for R_C=0.4



“Fake-Jet” contribution

“Fake” jets: signal in excess of background model from random association of uncorrelated soft particles (i.e. not due to hard scattering)



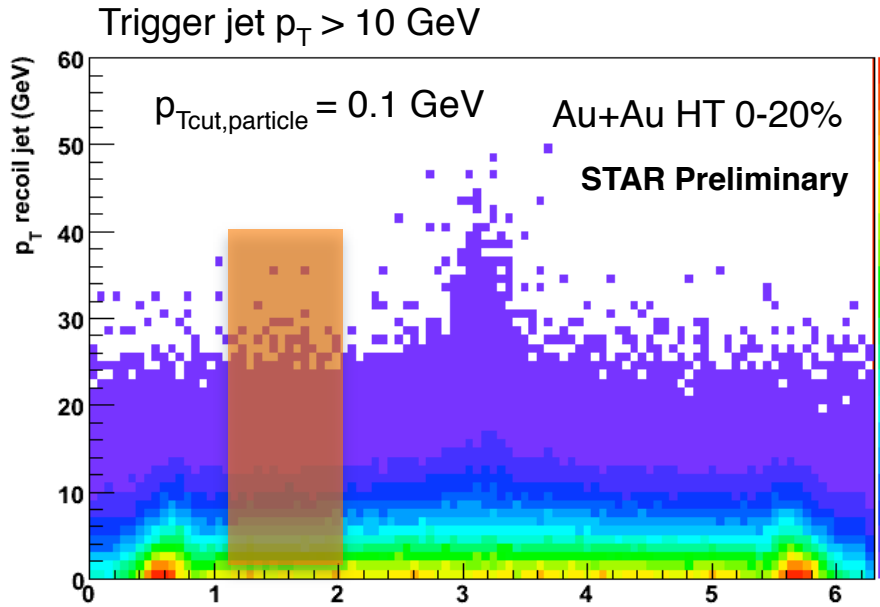
- **Inclusive jet spectrum**:

Spectrum of “jets” after randomizing HI event in ϕ and removing leading jet particle

- **Di-Jet / Fragmentation function:**

Background di-jet rate
= “Fake” + Additional Hard Scattering

Estimated using “jet” spectrum at 90 deg.



Spectrum Unfolding

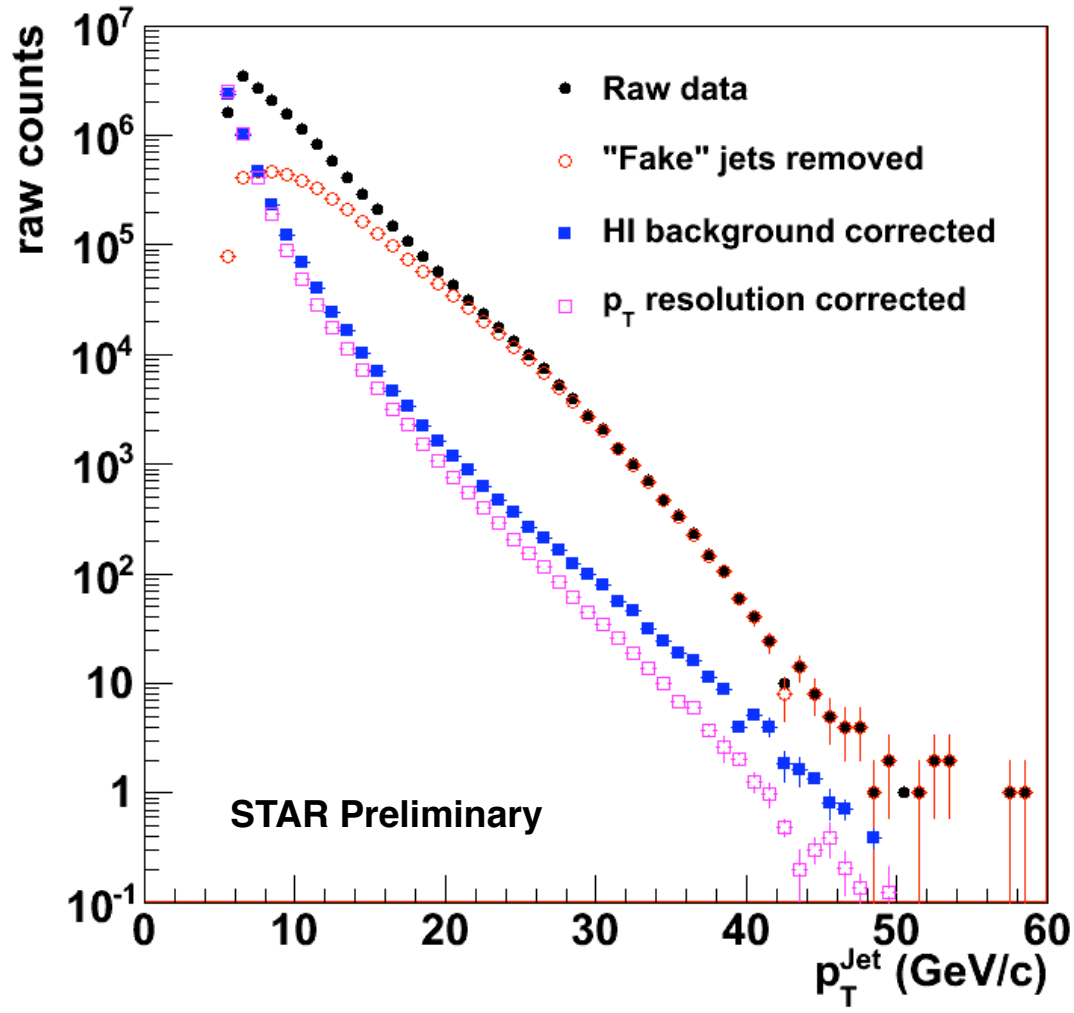
Corrections for smearing of jet p_t due to HI bkg. nonuniformities:

1) raw spectrum

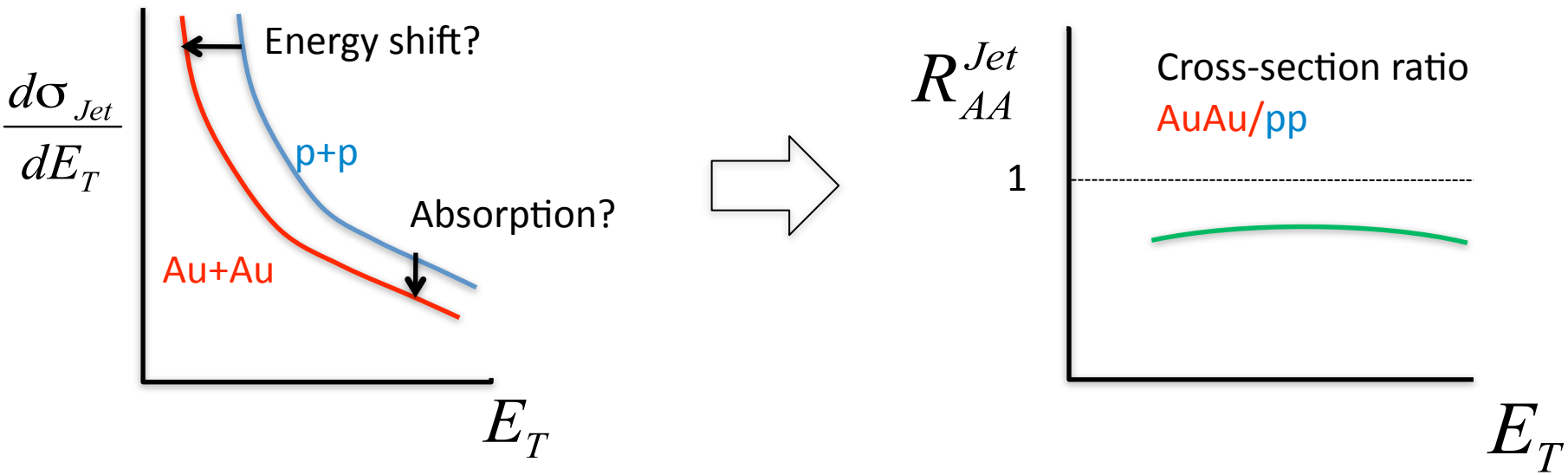
2) removal of “fake”-correlations

3) unfolding (bayesian) of HI bkg. fluctuations

4) correction for p_T resolution



What do we learn from the AuAu jet spectrum ?



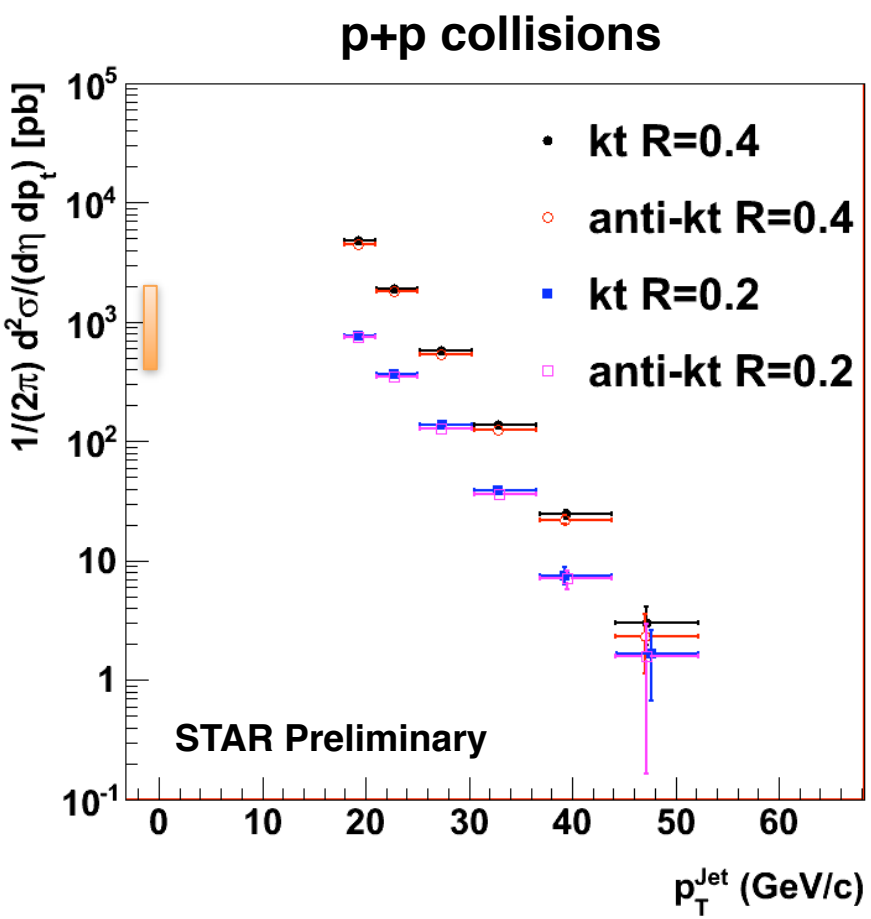
Momentum and energy is conserved even for quenched jets

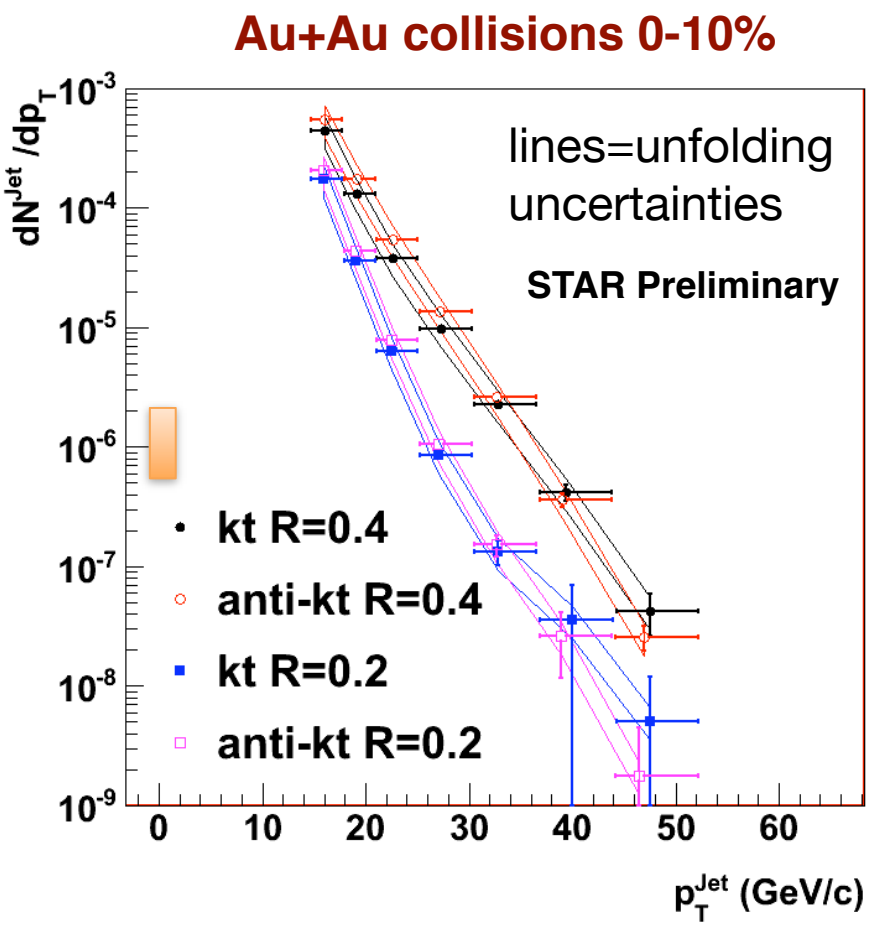
If full jet reconstruction in heavy-ion collisions is unbiased

⇒ Inclusive jet spectrum scales with N_{binary} relative to p+p

Caveat: Initial state nuclear effects at large x;
"EMC effect" can be measured in d+Au

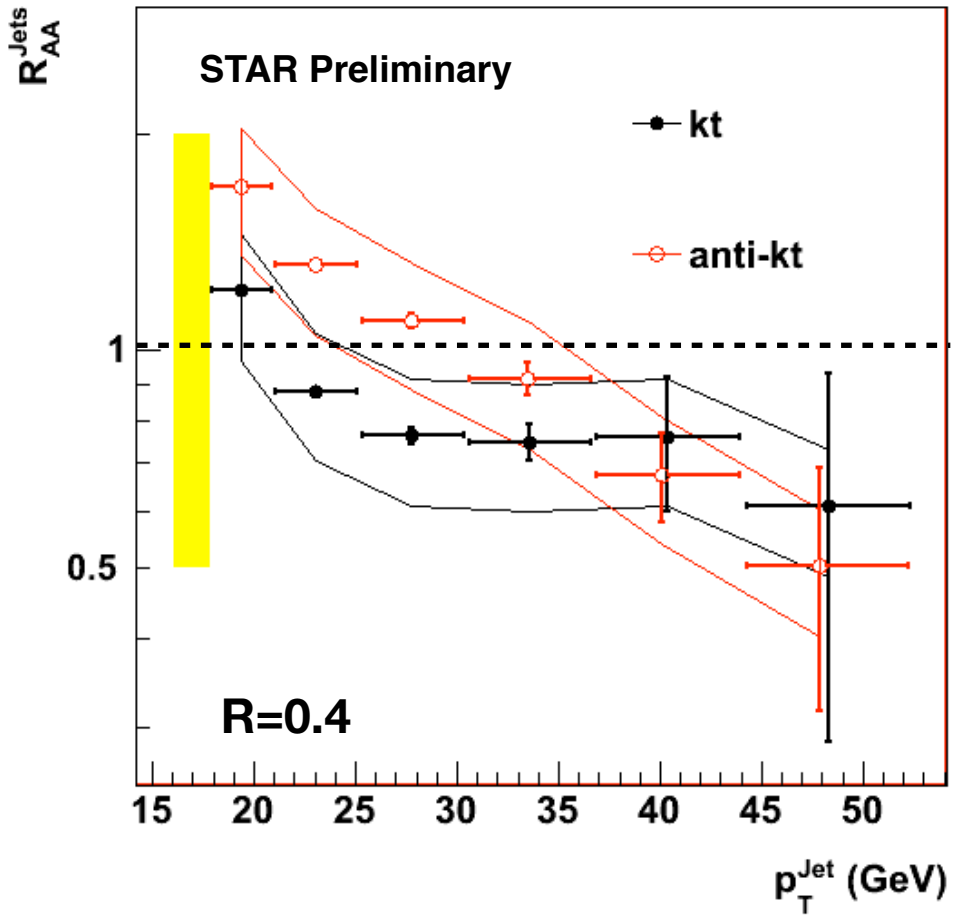
Inclusive jet x-section in central Au+Au





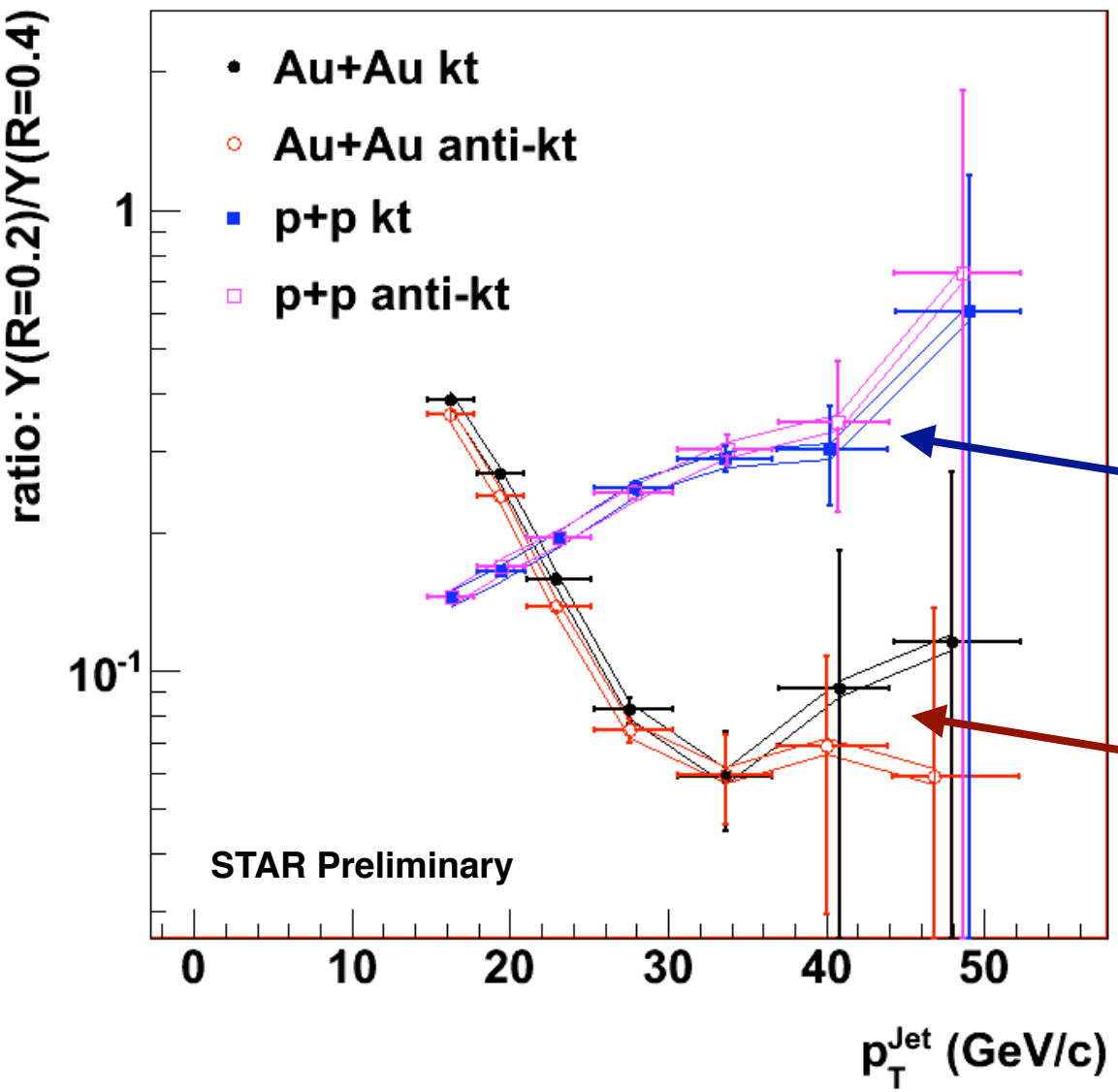
- **Inclusive Jet spectrum measured in central Au+Au collisions at RHIC**
- **Extended the kinematical reach to study jet quenching phenomena to jet energies > 40 GeV**

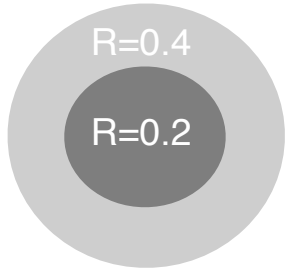
Jet R_{AA} in central Au+Au



- **We see a substantial fraction of jets**
  - in contrast to x5 suppression for light hadron R_{AA}
- **k_T and Anti-k_T known to have different sensitivities to background**

First look at the jet energy profile





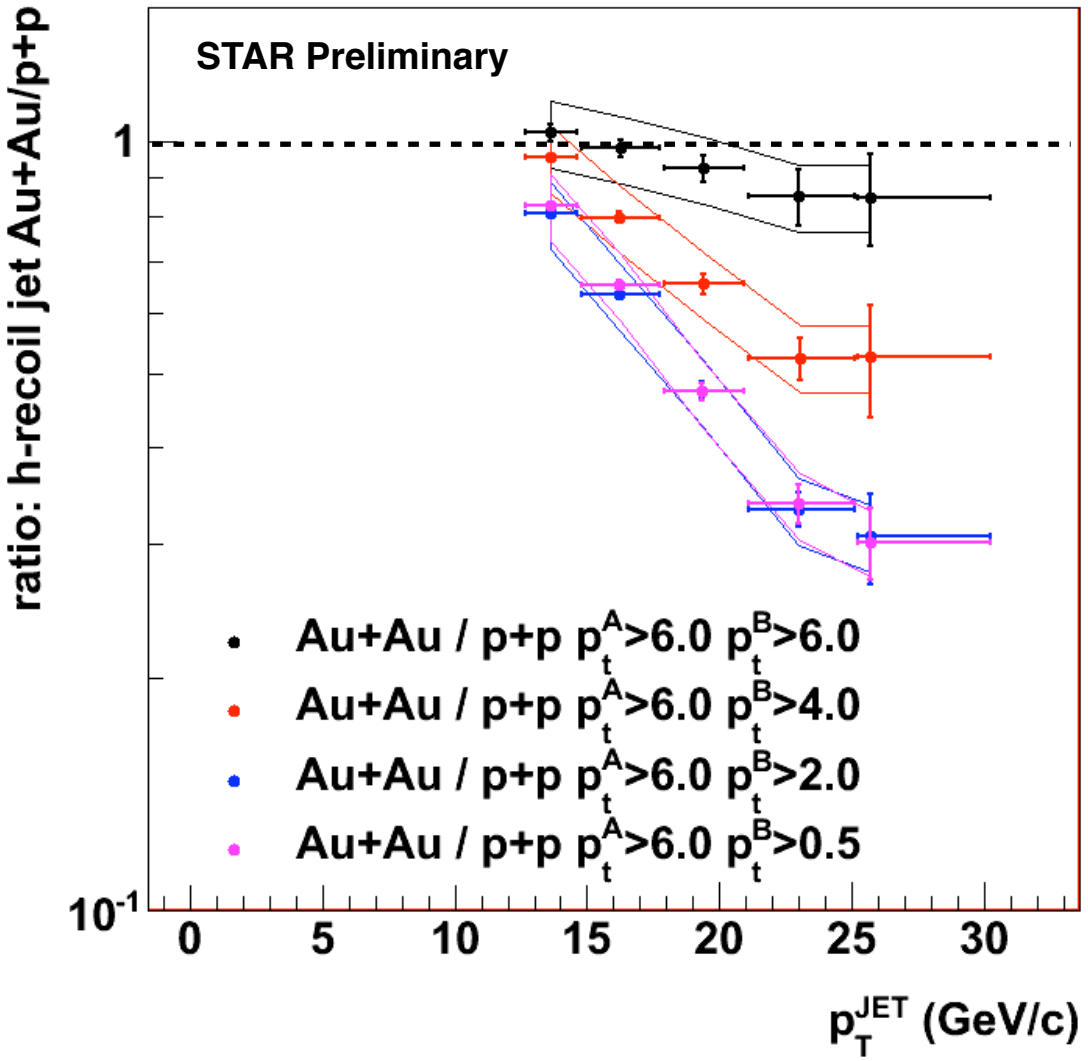
p+p: "Narrowing" of the jet structure with increasing jet energy

Au+Au: "Deficit" of jet energy of jets reconstructed with R=0.2

Strong evidence of broadening in the jet energy profile

Exploring pathlength dependence for recoil jets

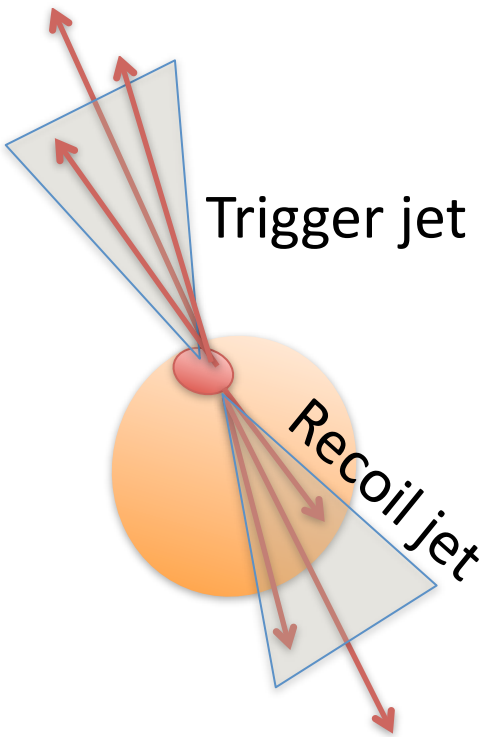
Trigger on high p_T π^0 and look at jet recoil spectrum

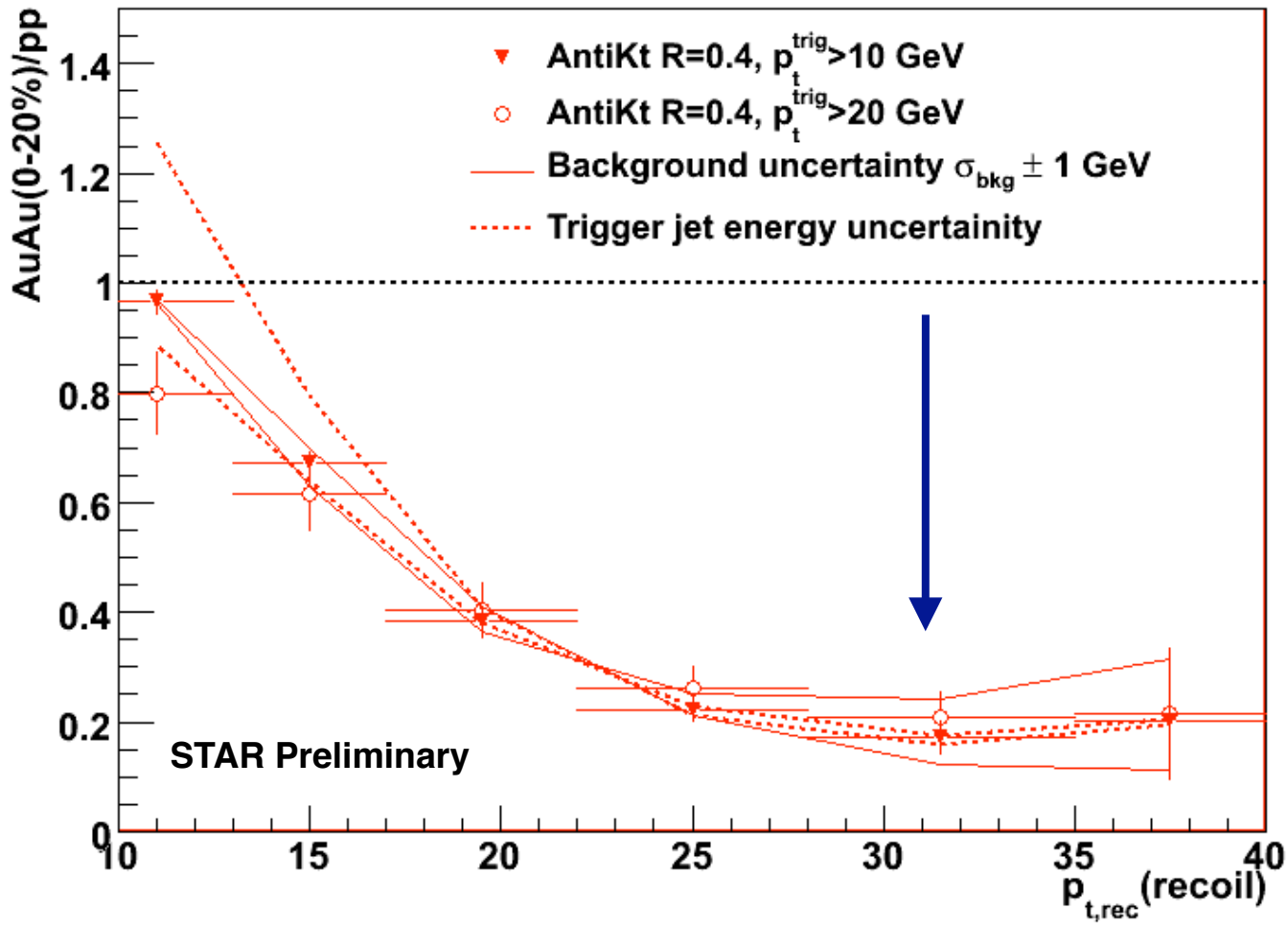


Increasing pathlength of recoil jets

Significant suppression in hadron-jet coincidence measurements of the unbiased recoil jet spectrum

Recoil jet spectrum R_{AA}

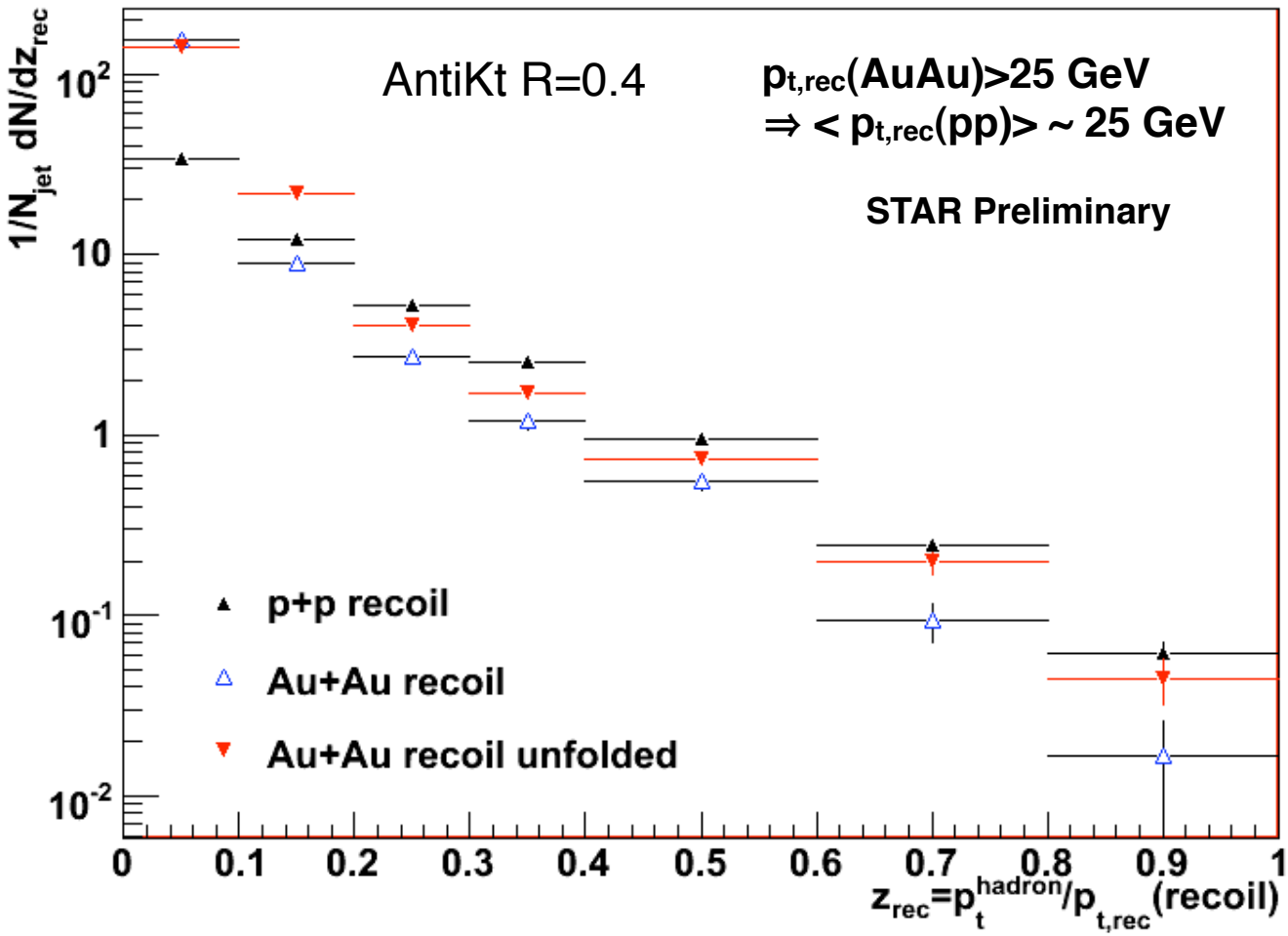


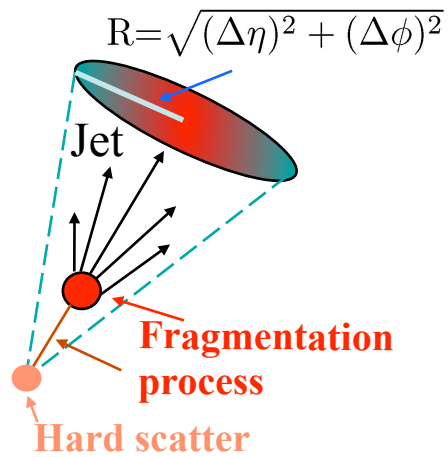


- Selecting unmodified trigger jet maximizes pathlength for the back-to-back jets: "extreme" selection of jet population
- Significant suppression in di-jet coincidence measurements

Recoil Fragmentation Function in Au+Au collisions

large uncertainties due to background
(further systematic evaluation needed)





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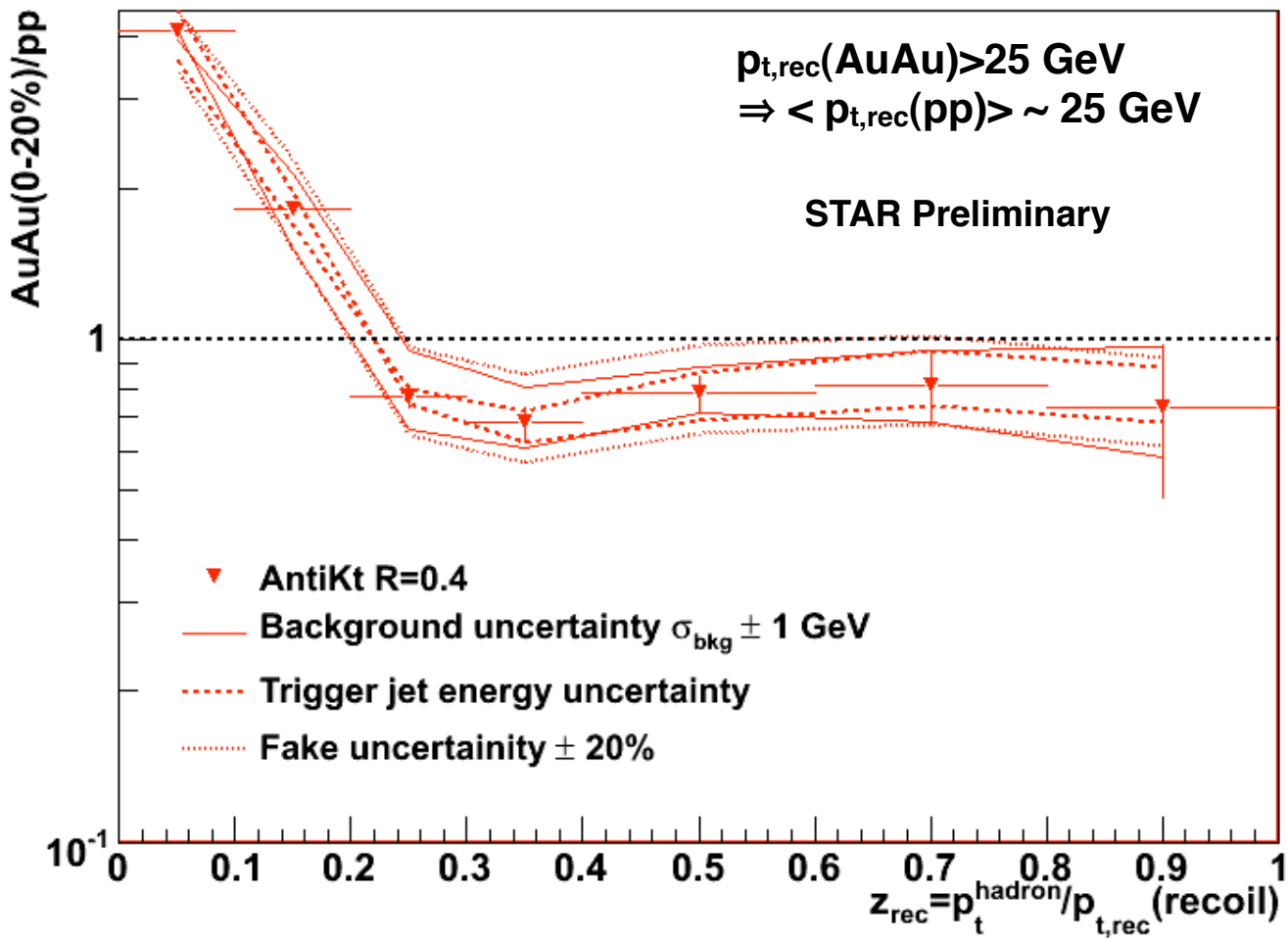
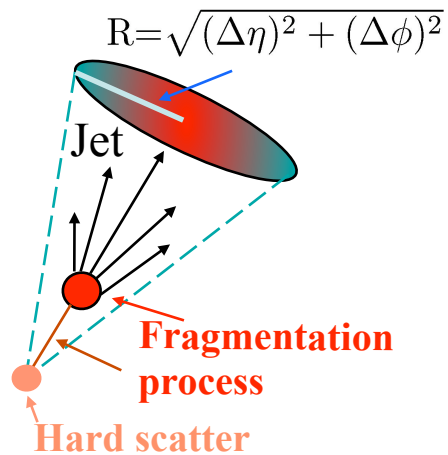
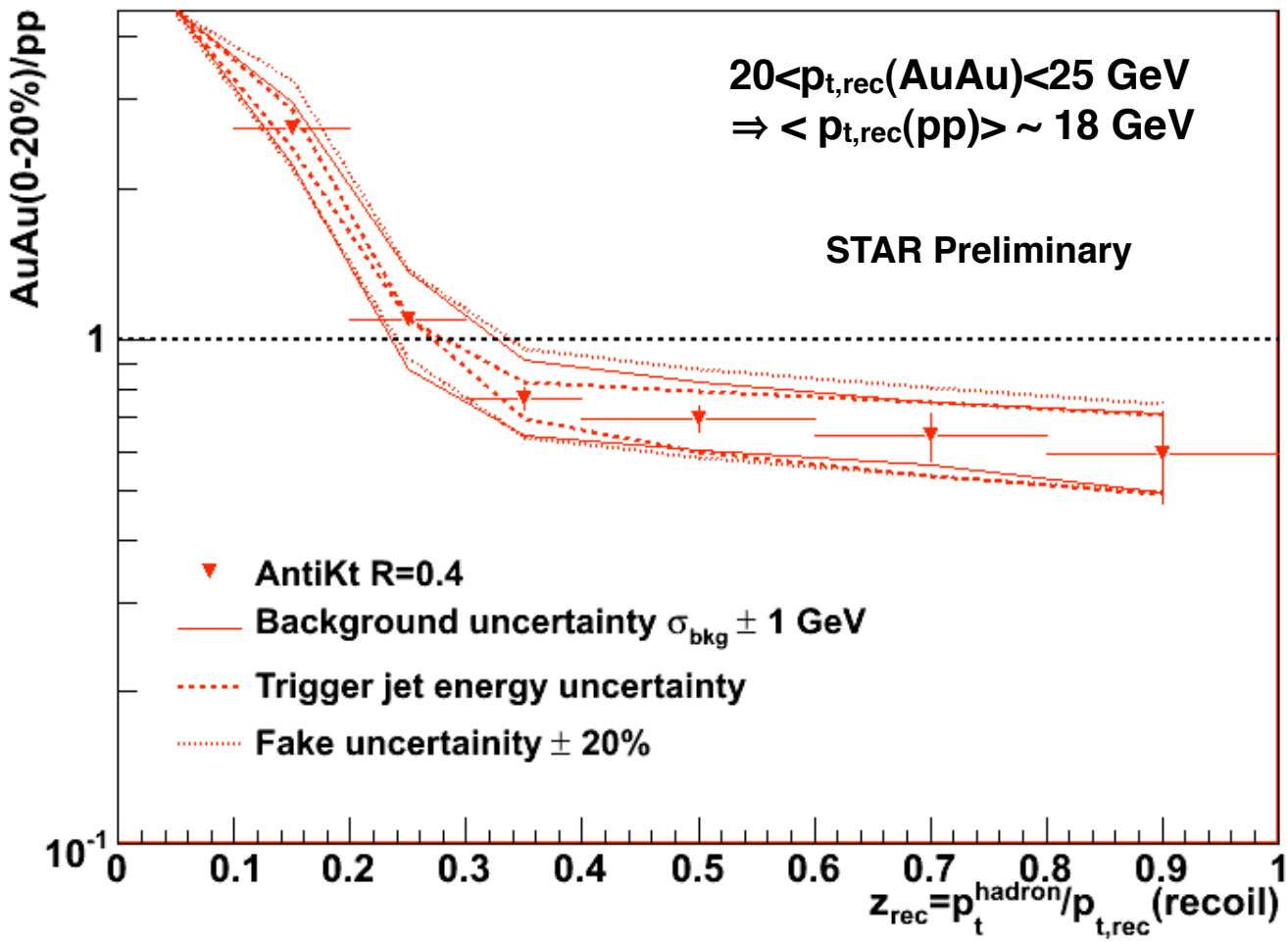
(further systematic evaluation needed)

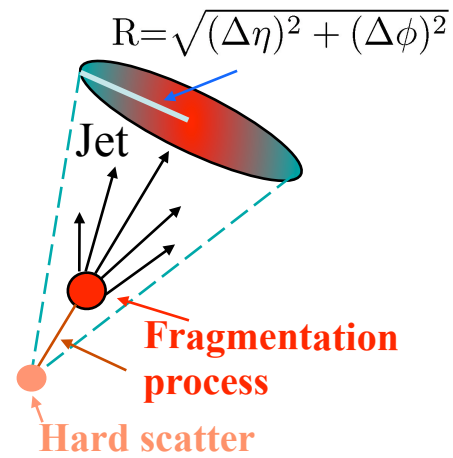




Recoil Fragmentation Function in Au+Au collisions

large uncertainties due to background
(further systematic evaluation needed)

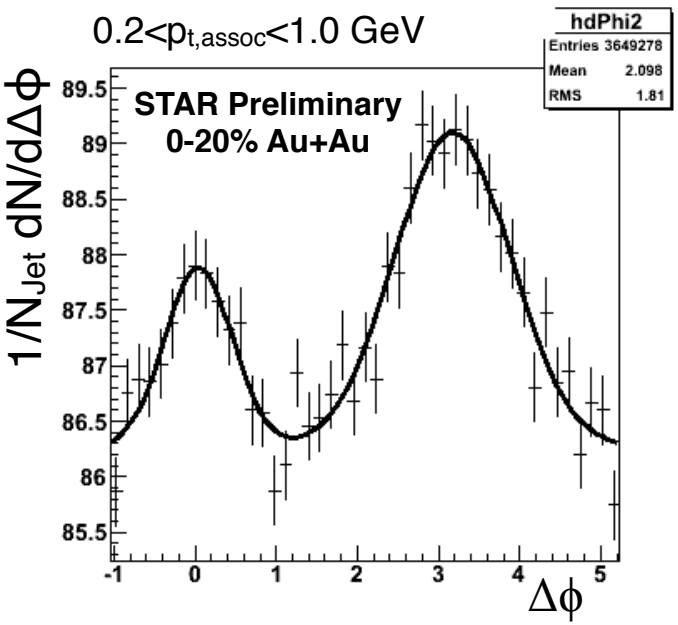


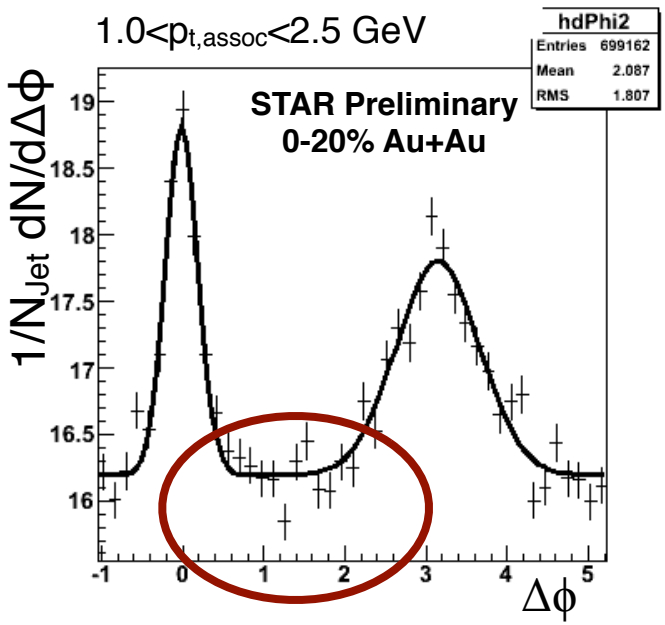


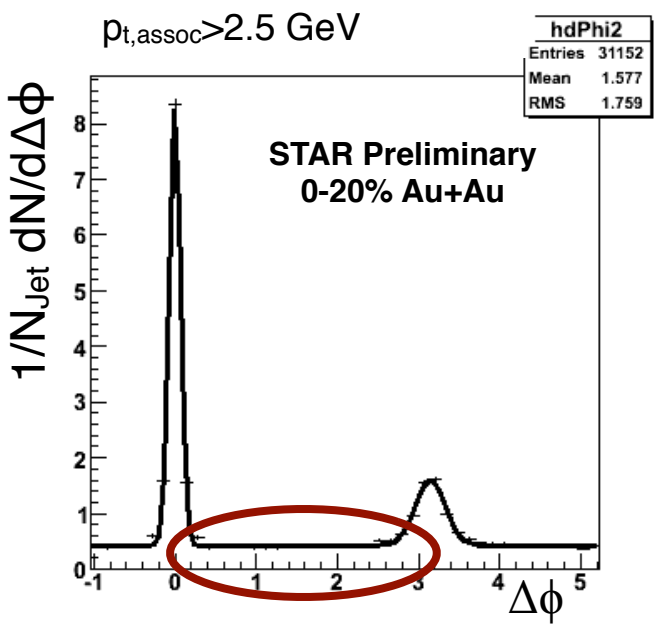
Indication of modification in the fragmentation function for lower jet p_t < $p_{t,rec}$(pp)> ~ 18 GeV

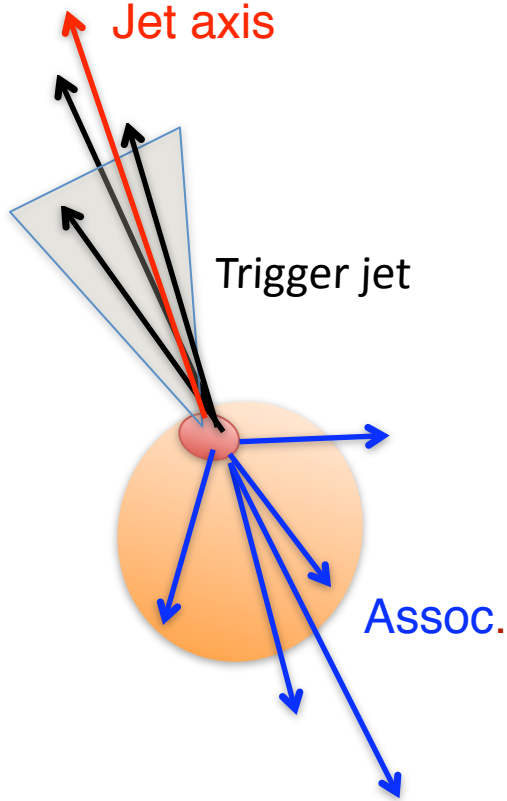
Unsubtracted Jet-Hadron correlations 0-20% Au+Au

High Tower Trigger (HT): tower 0.05x0.05 (ηxϕ) with E_t> 5.4 GeV









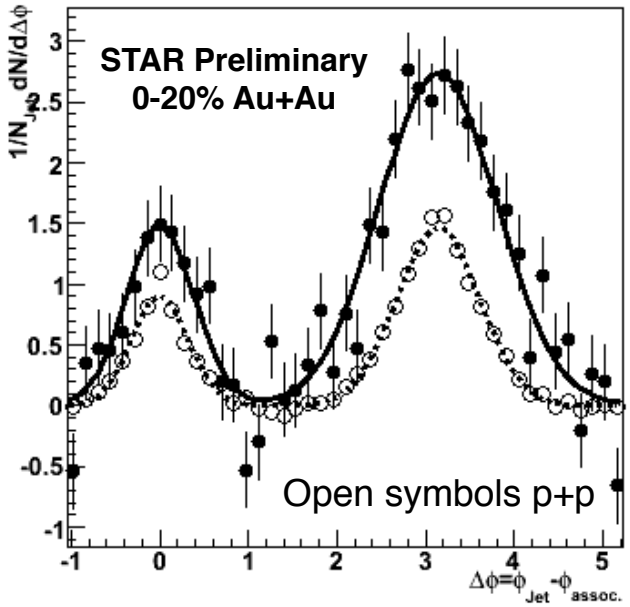
$\Delta\phi = \phi_{Jet} - \phi_{Assoc.}$

ϕ_{Jet} = HT trigger jet-axis found by Anti-kt with R=0.4, $p_{t,cut}$>2 GeV and $p_{t,rec}$(jet)>20 GeV

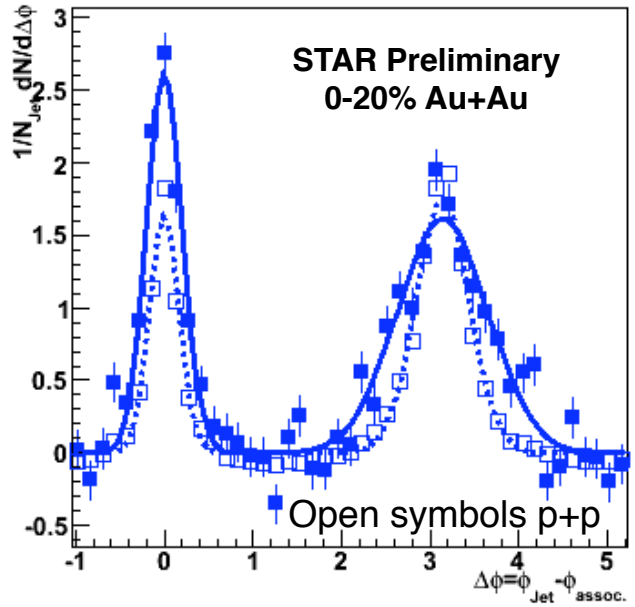
- **Jet v_2 contribution under investigation**
- **Use 2 gaussian + constant fit to describe the azimuthal correlation function**

Jet-hadron correlations 0-20% Au+Au vs. p+p

$0.2<p_{t,assoc}<1.0$ GeV



$1.0<p_{t,assoc}<2.5$ GeV

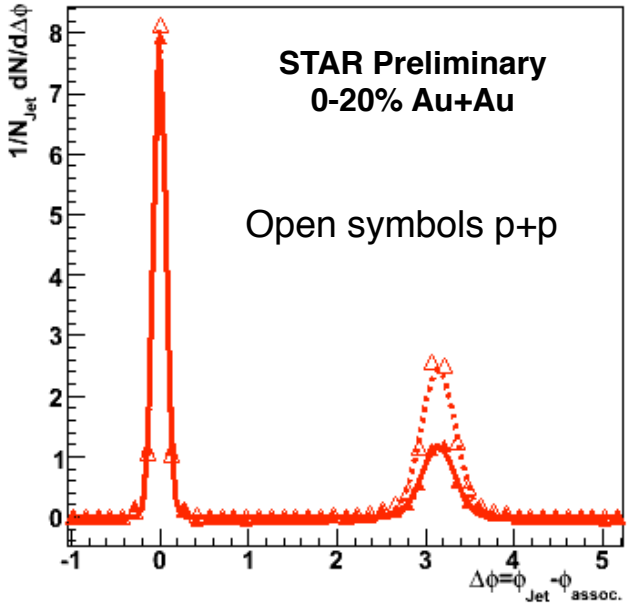


High Tower Trigger (HT): tower 0.05x0.05 (ηxφ) with E_t> 5.4 GeV

$\Delta\phi=\phi_{Jet}-\phi_{Assoc.}$

ϕ_{Jet} = HT trigger jet-axis found by Anti-kt with R=0.4, $p_{t,cut}$>2 GeV and $pt_{,rec}$(jet)>20 GeV

$p_{t,assoc}$>2.5 GeV



- **Significant broadening and softening visible on the recoil side**
- **"Modified fragmentation function"**
- **"Not" visible in di-jets, suggesting that current jet-finding approach is biased towards less interacting jets and/or underestimation of jet energy**

Summary

- Jet reference measurements (p+p and d+Au) well understood
- Significantly larger fraction of the jet population measured via full-jet reconstruction wrt to single inclusive measurements
- Strong evidence of broadening in the jet energy profile
- Significant suppression of hadron-jet and di-jet coincidence yields in central Au+Au collisions
- Only small modifications of the recoil-jet fragmentation function
- Jet-hadron correlations show a significant broadening and softening of the recoil jet ⇒ "modified" fragmentation function

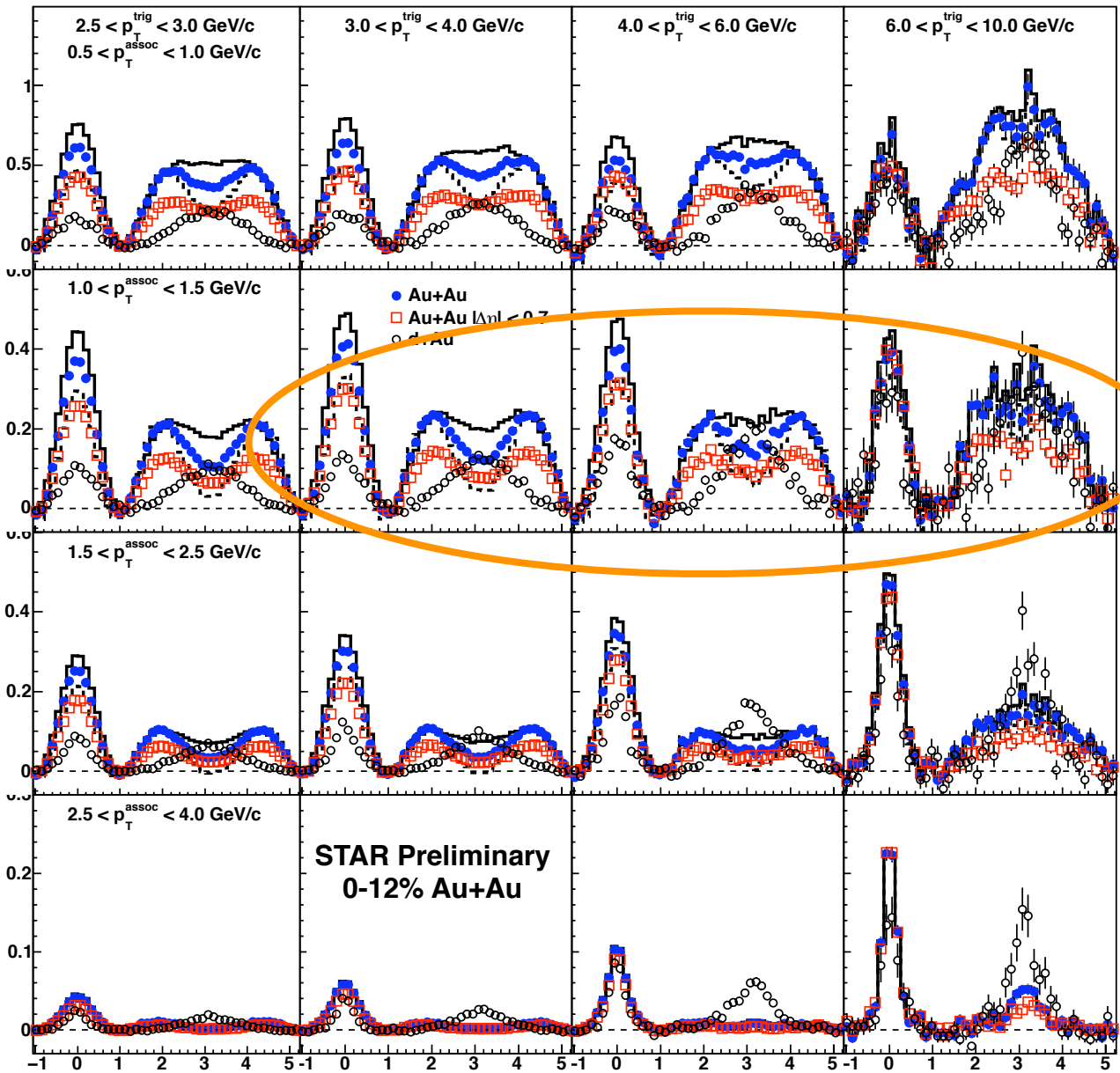
<u>Picture emerging:</u> Current results from full-jet reconstruction in heavy-ion collisions at RHIC can be explained (qualitatively) by significant broadening of the jet structure due to partonic energy loss

Backup

Di-hadron correlations: Mach-Cones @ RHIC ?

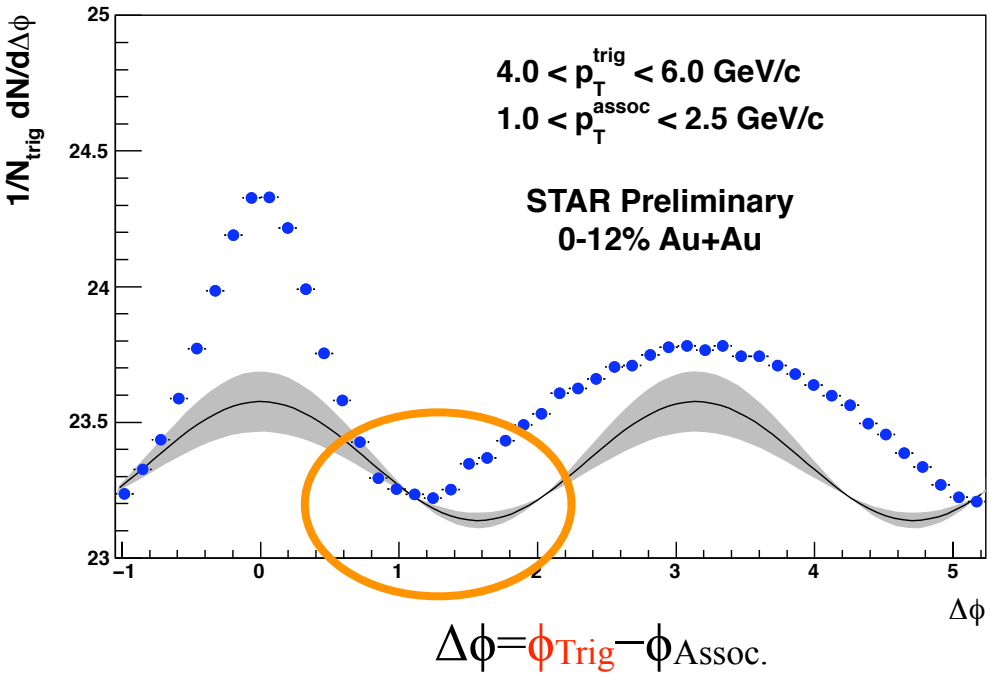
Increasing $p_{t,trigger}$

Increasing $p_{t,assoc}$



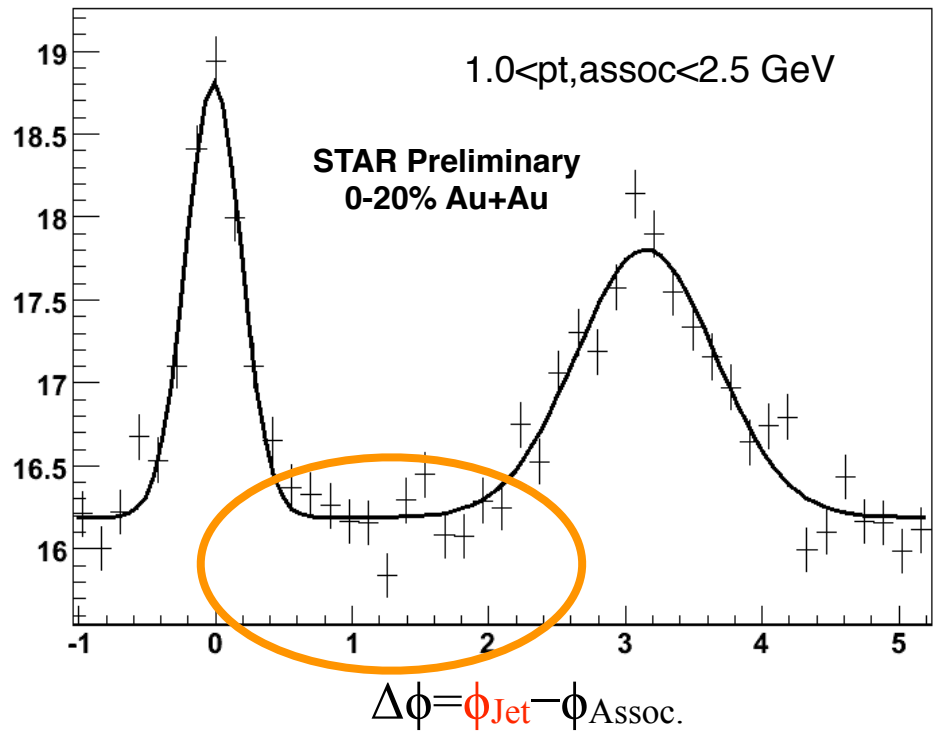
Away-side structure dep. on pt,trig !

Unsubtracted Jet-hadron vs. di-hadron



$\Delta\phi = \phi_{Trig} - \phi_{Assoc.}$

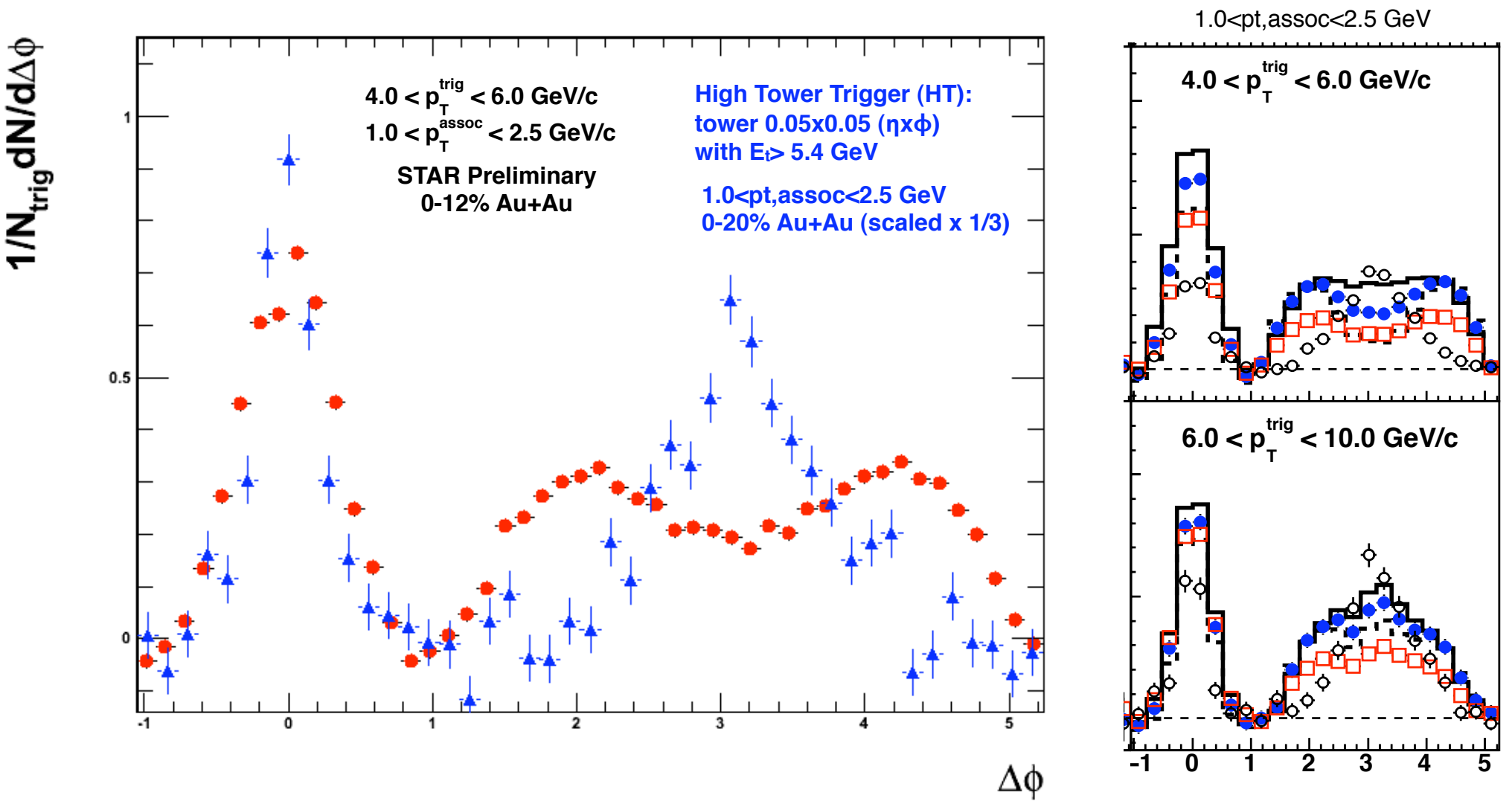
High Tower Trigger (HT): tower 0.05x0.05 (ηxφ) with E_t> 5.4 GeV



$\Delta\phi = \phi_{Jet} - \phi_{Assoc.}$

- No apparent v2 modulation in Jet-hadron vs. di-hadron
- jet axis not correlated wrt to the event plane (?)
- v2 unsubtracted di-hadron correlation does not show mach-cone like structures, only after v2 subtraction (!?)

Away-side structure: di-hadron vs. jet-hadron



Jet-hadron away-side significantly narrower than di-hadron
=> can not be explained by punch-trough only/ no wings (!)

Discussion

Two scenarios:

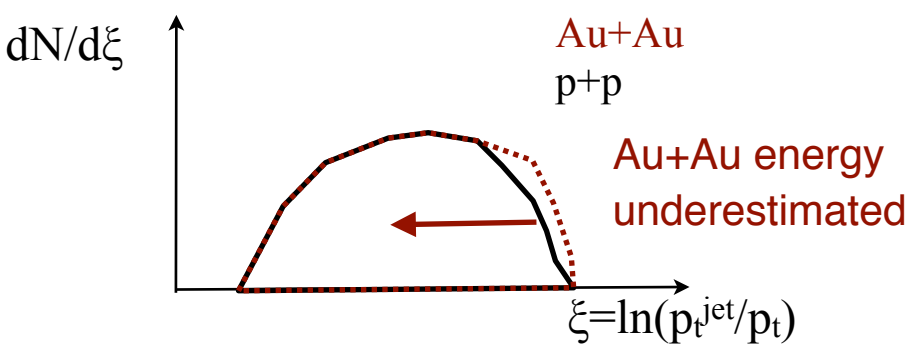
1) Jet-energy bias due to energy loss and p_t^{cut}:

Pythia-based correction underestimates jet energy carried by low p_t particles

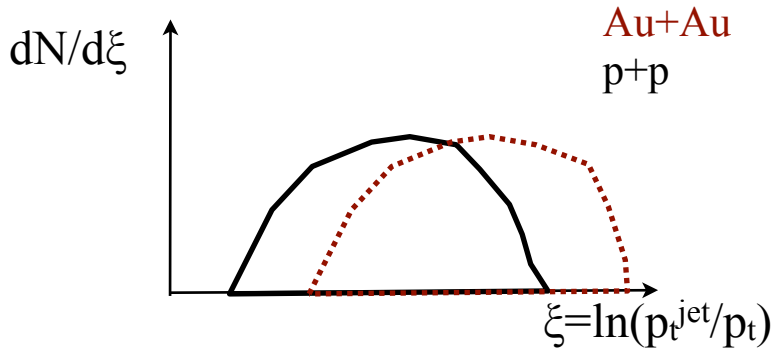
→ **Au+Au jet energy is underestimated**

Large Au+Au quenching:

observed distributions



true distributions



2) "black-and-white":

Some fraction of jets quenched so much that they are lost; surviving jets are unmodified

We have all the tools and data needed to address and distinguish between these two scenarios, but MC quenching model needed !